ISSN 3009-2892 (Online)

UDC 620.9
621.31

Elektroprivreda

Electric Power Industry Journal

2023

Godina 1, Broj 1
Volume 1, Issue 1

SPECIAL EDITION

CIRED Serbia

ISSN 3009-2892 (Online)
UDC 620.9
621.31

Elektroprivreda

Electric Power Industry Journal

Scientific and professional journal of the joint-stock company "Elektroprivreda Srbije"
in co-publishing with the Electrotechnical Institute "Nikola Tesla" Belgrade

Volume 1, Issue 1

Content

EXECUTIVE PUBLISHER:
JOINT STOCK COMPANY „ELEKTROPRIVREDA SRBIJE“ BELGRADE
11 000 Belgrade, Balkanska str. 13
Internet presentation: www.eps.rs
Editor-in-Chief phone: +381-11-365-23-63
E-mail: epijournal.editor@eps.rs
The Journal web platform: https://epijournal.eps.rs

CO-PUBLISHER:
ELEKTROTECHNICAL INSTITUTE „NIKOLA TESLA“ BELGRADE
11 000 Belgrade, Koste Glavinića str. 8a
Internet presentation: www.ieent.org
Phone: +381-11-39-52-000
Fax: +381-11-36-90-487

FOR EXECUTIVE PUBLISHER:
Dušan Živković, Dipl. El. Ing.
Acting General Manager of EPS JSC

FOR CO-PUBLISHER:
Dr. Dragan Kovačević, Dipl. El. Ing.
Director of ETI „Nikola Tesla“

EDITOR-IN-CHIEF:
Dr. Vladimir M. Shiljkut (Šiljkut), Dipl. El. Ing.

National Library of Serbia, Belgrade

Časopis „Elektroprivreda“
Electric Power Industry Journal
Editor-in-Chief
Dr Vladimir M. Šiljkut,
scientific associate

The Journal is published twice a year
ISSN 3009-2892 (Online) Open Access
COBISS.SR-ID - 121874441

Editorial Word

Dear readers and collaborators,

The "Elektroprivreda" Journal began to be published back in 1948, at first under a different name, as a professional journal in which numerous professional and even scientific manuscripts were published, presenting experiences from the electric power industry in the entire territory of former Yugoslavia. The Journal was published continuously, mostly quarterly, in printed form, during 64 years period. Therefore, it can be freely said that he was both a contemporary and a witness to the country's electrification, accelerated development, but also the latter's serious problems, as well as the numerous transformations of the electric power industry of the entire region, and wider interconnection. Therefore, it is not surprising that during its long history, it has gained the rank of a prominent Journal of national importance. The last issue of the old "Elektroprivreda" Journal, however, was published in 2011. Namely, the Journal faced organizational and technical problems and the work on the preparation and publication of new editions was soon stopped.

With a vision of strategic development and understanding that without the solid cooperation of people from the profession and practice with scientific and research institutions and innovative centers, as well as without the open exchange of their opinions and experiences, there is no further progress in the field of power engineering, the management of EPS in 2022 and at the beginning of 2023. made two significant decisions. The first is the organization and start of work of the EPS Scientific Council, which consists of representatives of the academic, scientific-research community and EPS employees with academic and scientific titles. The second is the decision to restart the publication of the "Elektroprivreda" – Electric Power Industry Journal, as a scientific and professional journal, according to a new, broader concept and bilingually, in Serbian and English. The EPS Scientific Council and the new "Elektroprivreda" will present fields, platforms and tools for displaying experiences, constructive expression and confrontation of views, expert discussions and formulating advice and conclusions on issues of strategic development and opting for new technologies. Namely, we are convinced that only in this way the electric power industry in Serbia and beyond, faced with the inevitability of decarbonization, digitization and the transition to sustainable development, will be able to find adequate and optimal technical-technological, legal-economic and organizational-business answers to all challenges.

In the line with these ideas, the Editorial Board invites you to cooperate and keeps an open invitation for the submission of your manuscripts, which will be reviewed in detail by eminent experts in the fields to which the manuscripts relate. We also invite interested experts with experience in reviewing to apply as reviewers of manuscripts that will be submitted for publication in the Journal. We also invite all readers to get involved in our work, by sending written discussions, in case they feel the need to comment on some of the published texts in the Journal, to attach a polemic or provide some similar contribution. Namely, only with the interest and valuable, active participation of the readership, authors and reviewers, will it be possible not only to successfully restart the "Elektroprivreda" – Electric Power Industry Journal, but also its sustainability, regularity of publication, topicality and quality.

On behalf of the Editorial Board,

Vladimir Šiljkut (Shiljkut), Ph.D.
Editor-in-Chief

Guest Editor-in-Chief Preface

Dear readers,

In front of you is the first issue of the renewed "Elektroprivreda" – Electric Power Industry Journal. The decision of the Joint Stock Company "Elektroprivreda Srbije" (EPS JSC) to restart its publication was preceded by the successful 13th Conference organized by the National Liason Committee for Electricity Distribution Networks, CIRED Serbia, in Kopaonik mountain, in September 2022. Considering the earlier practice of the old Journal, within the framework of the formally adopted Decision of EPS JSC, it is foreseen that awarded papers from the previously held CIRED Serbia Conference will be published in odd calendar years, but now within the framework of a separate, Special Edition, textually expanded by at least a third compared to the awarded paper, qualitatively improved and additionally peer-reviewed, according to the same procedure as provided for manuscripts nominated for publication in regular editions of the Journal. Due to the circumstances and the aforementioned sequence of events, the first issue of the renewed Journal is exactly the Special Edition, dedicated to the works awarded at CIRED Serbia 2022.

The National Liason CIRED Committee of Serbia, following the example of the international CIRED, has six Expert Commissions (EC). National Conferences with regional participation are held biennially, and on that occasion, each EC awards a prize for the most notable paper in the areas of electricity distribution activities that EC deals with. Also, the possibility of awarding a seventh prize, for a paper that shows technical innovation, is foreseen, and it can be awarded to just one paper, at the level of the entire CIRED Serbia National Liason Committee. It was exactly the case at the 13th Conference – that prize was also awarded.

The authors of all papers awarded in September 2022 responded to our kind invitation and the invitation of the permanent Editorial Board of the Journal. They submitted manuscripts with expanded and improved versions of their papers. After the procedure of in detail review of manuscripts, reconciliation of authors with reviewers, you are presented with a selection of those award-winning papers that have obtained at least two positive reviews and received final approval for publication.

I hope that the awarded papers, published in this Edition in their expanded and improved versions, will make a scientific and professional contribution to the electric power industry in Serbia and encourage authors from Serbia and other countries to publish their manuscripts in the new magazine "Elektroprivreda" – Electric Power Industry Journal in the future.

On behalf of the Guest Editorial Board
of the Special Edition of the Journal,

Zoran Simendić, Ph.D.
Guest Editor-in-Chief

UDC: 621.383.51
621.316

Nikola N. Krstić[1], Dragan S. Tasić[1]

Method for determining the optimal location and configuration of the system consisting of photovoltaic and energy storage system considering the reduction of losses in the distribution network

[1] Faculty of Electronic Engineering in Niš, Niš, Serbia*

Category of article: Original scientific research article

Highlights

- This paper considers the reduction of losses in the distribution network by connecting the system consisting of photovoltaic (PV) and energy storage system (ESS).
- The optimal location and optimal power of the system consisting of PV system and ESS is determined, taking into account the minimization of losses in the distribution network.
- Sizing of the PV system and ESS is carried out.
- The influence of the discrepancy between the actual and expected values of load and solar irradiation on the increase of losses in the distribution network and the change in the state of charge of ESS

Abstract

In this paper two-step method for determining the optimal location and configuration of the system consisting of PV system and ESS, considering the reduction of losses in distribution network, is presented. First step takes into account the daily load diagram and uses the metaheuristic particle swarm optimization method (PSO) to determine the optimal location and optimal power during the day of the system consisting of PV system and ESS in order to minimize the losses in distribution network. In the second step of the procedure, the individual powers of PV system and ESS are obtained and their configuration (sizing) determined. This is done by iterative procedure using the optimal values of combined power of these two systems during the day, obtained in the first step, and the shape of daily solar irradiation diagram of the PV system for the clear day. The configuration procedure is explained in detail, determining the maximum power of PV system, maximum power of ESS and energy capacity of ESS. In addition, the impact of the difference between the actual and the expected load diagram and the influence of the reduction of solar irradiation during the day on the increase of losses in the distribution network and the change in the state of charge of the ESS are considered. The paper considers cases with different load diagrams and different levels of ESS efficiency. All results are obtained using IEEE radial distribution network with 33 nodes.

Keywords

Photovoltaic (PV) System, Energy Storage System (ESS),

Particle Swarm Optimization Method (PSO), Losses in the Distribution Network

Note:
This article represents an expanded, improved and additionally peer-reviewed version of the paper "*Optimal location and configuration of the system consisting of photovoltaic and energy storage system considering the reduction of losses in distribution network*", awarded by Expert Committee EC-4 *Distributed Generation and Efficient Use of Electricity* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

Received: April 5th, 2023 Reviewed: April 25th, 2023
Modified: April 28th, 2023 Accepted: May 4th, 2023
*Corresponding author: Nikola N. Krstić
E - mail: nikola.krstic@elfak.ni.ac.rs

1. INTRODUCTION

Increasing environmental awareness has caused efficiency improvements and the use of green technologies to become one of the basic requirements and priorities set when considering power system operation. In meeting these requirements, renewable energy sources play a significant role, with numerous attempts made to facilitate their power system integration and operational improvements [1]. One particularly important form of their application is connection to the distribution network [2] where they play the role of distributed generation. Through this, renewable energy sources bring generation closer to the consumption and reduce transmission losses [3]. However, due to their intermittent character, they are often unable to achieve the required power that would bring the desired network efficiency increase. One of the solutions to this problem, especially in cases where distributed generation and load are largely mismatched, is the use of ESS [4]-[5].

Specifically, this paper discusses the distribution network efficiency improvements, using loss reduction [6], by utilising a system consisting of a PV system and an ESS [7]. This combined system operates like a distributed generation with possible control of the output power to the distribution network [8]-[9]. This power facilitates load shedding of certain parts of the distribution network, especially the supply ones, reducing pertaining losses. Distribution network power flows and currents along its lines are determined by an iterative method for power flows calculation in radial distribution networks [10]. To minimize distribution network losses, in this case, it is necessary to correctly locate the mentioned system and ensure at all times an adequate value of its output power [8]. The optimal location and power that need to be injected into the distribution network by a system composed of a PV system and an ESS, to minimize pertaining losses, [3], [11], were determined using the PSO metaheuristic optimization method, [12]-[15], considering the expected daily load diagram. Based on the obtained optimal power of the system during the day and the daily solar irradiation diagram of the PV system in the case of a clear day, individual powers of the PV system and ESS have been determined, together with their optimal configuration, i.e. sizing [11], [16]. Here, the required maximum powers of the PV system and the ESS were determined, along with the required energy capacity of the ESS, for different diagrams and load types, using different ESS efficiency levels.

The procedure used to determine the configuration of a system consisting of a PV system and an ESS is of an iterative type, where the maximum power of the PV system is determined based on the assumed values for the ESS charging/discharging periods [17], on the basis of which the ESS charging/discharging periods are more accurately determined in the next iteration. Initial values of the ESS charging/discharging periods are determined based on the shape of the daily load diagram of the distribution network and the daily solar irradiation diagram of the PV system. The iterative procedure ends when the ESS charging/discharging periods have the same value in two adjacent iterations. The procedure applied to determine the optimal location and configuration of a system consisting of a PV system and an ESS requires knowledge of the distribution network daily load diagram and the PV system solar irradiation diagram. Due to their stochastic nature, these diagrams cannot be predicted with certainty [18], which is why the optimal system configuration is performed based on their most probable values, including the expected load diagram and solar irradiation diagram of the PV system on a clear day. For this reason, the influence of the discrepancy between actual and expected (predicted) load values, as well as the influence of the PV system solar irradiation reduction due to cloud cover during the day, on the network losses increase and the change of the ESS state of charge has also been examined. [19].

2. DEFINING THE OPTIMIZATION PROBLEM AND CRITERION FUNCTION

Reducing distribution network losses by using a system composed of a PV system and an ESS is a nonlinear optimization problem with constraints. The non-linearity arises from the non-linear dependence of the distribution network losses on the injection power of the combined system and non-linear constraints that need to be met.
Control variables in this optimization problem are the location and the mean hourly power of a system composed of a PV system and an ESS. Constraints of the control variables have been given by the following relations:

$$i \in \{i_1, i_2, \ldots i_n\} \tag{1}$$

$$P_{min}(k) < P(k) < P_{max}(k) \tag{2}$$

where i is the distribution network node index where the system consisting of a PV system and an ESS is connected, while $P(k)$ is the mean hourly power injected by this system into the distribution network in the k-th hour. The set of node indexes where it is possible to connect the mentioned system is given as $\{i_1, i_2, \ldots i_n\}$, while $P_{min}(k)$ and $P_{max}(k)$ are its minimum and maximum power in the k-th hour, determined by the minimum and maximum power of the PV system and ESS ($P_{min}(k) = P_{PVmin}(k) + P_{ESSmin}(k)$, $P_{max}(k) = P_{PVmax}(k) + P_{ESSmax}(k)$).

The dependent variables appearing in this optimization problem are the power of the PV system, power of the ESS, the ESS state of charge, the current along the distribution network lines and the voltage in its nodes.

Constraints of the dependent variables are determined by the minimum and maximum powers of the PV system and the ESS, the maximum operating current and the allowed voltage range of the distribution lines, as well as the allowed range of the ESS state of charge, which is given by the relations (3)-(7):

$$P_{PVmin}(k) < P_{PV}(k) < P_{PVmax}(k) \qquad (3)$$

$$P_{ESSmin}(k) < P_{ESS}(k) < P_{ESSmax}(k) \qquad (4)$$

$$I < I_{max} \qquad (5)$$

$$V_{min} < V < V_{max} \qquad (6)$$

$$SOC_{min} < SOC < SOC_{max} \qquad (7)$$

where I and V are the distribution network current and voltage, while SOC is the ESS state of charge.

Powers $P_{PV}(k)$ and $P_{ESS}(k)$ are the mean one-hour powers of the PV system and ESS in the k-th hour, which, similar to the other quantities, must be between their minimum ($P_{PVmin}(k)$, $P_{ESSmin}(k)$) and maximum values ($P_{PVmax}(k), P_{ESSmax}(k)$). In this paper, limiting values for ESS powers (maximum charging power and maximum discharging power) do not represent a limiting factor to obtain an optimal solution and have the same value throughout the day. In contrast, the upper limit value for the power of the PV system $P_{PVmax}(k)$ depends on the ordinal number of hours in day k, and follows the shape of the daily solar irradiation diagram of the PV system. Lower limit value for PV system power $P_{PVmin}(k)$ is equal to zero for every hour of the day.

For the obtained ESS operating modes to be sustainable in time, when determining the optimal system configuration, equal states of charge at the beginning (SOC_0) and the end (SOC_T) of the operating cycle (day) are used. For this purpose, an additional constraint related to the ESS state of charge is used:

$$SOC_T - SOC_0 = 0 \qquad (8)$$

The optimization problem solution is necessary to enable the distribution network loss minimization. For this reason, a single-parameter criterion function equal to the mean daily power of distribution network losses was used, given by the relation (9):

$$C = \frac{1}{24} \cdot \sum_{k=1}^{24} \sum_{j=1}^{m} 3 I_{k,j}^2 R_j \qquad (9)$$

where: $C -$ criterion function, whose minimization needs to be performed, $I_{k,j} -$ effective current value in the k-th hour along the j-th distribution network section, $R_j -$ active resistance of the j-th distribution network section, $m -$ total number of distribution network sections.

3. SOLVING THE OPTIMIZATION PROBLEM AND DETERMINING THE OPTIMUM SYSTEM CONFIGURATION

In order to obtain an optimal location and configuration of the system consisting of a PV system and an ESS, it is first necessary to solve the set optimization problem. Solving this optimization problem comes down to finding the optimal values for the location and power of the system consisting of a PV system and an ESS to achieve the distribution network loss minimization. The metaheuristic optimization method of PSO was used to obtain the optimal location and the optimal mean hourly power during the day of the combined system. The advantage of PSO and metaheuristic optimization methods in general is their flexibility and possible application to a wide range of different optimization problems.

3.1 Solving the optimization problem

As mentioned, PSO was used to solve the set optimization problem. PSO belongs to population metaheuristic optimization methods and is inspired by the foraging process of flocks of birds in nature. A population consists of a set of individuals, each of which represents a vector of control variables and a potential solution to an optimization problem. Individuals in the population communicate with each other and move towards the one in the place with the largest amount of food, i.e. that has the lowest criterion function value. To facilitate better space search where the optimal solution can be found, the individual movement direction is not influenced only by the location with the largest amount of food found until then (g_{best}), but also by the location with the largest amount of food that individual had found until then (p_{besti}). In this way, in each subsequent iteration, the individuals are closer to finding the place with the largest amount of food, and thus the smallest criterion function value. The individual that has the smallest criterion function value at the end of the optimization process is also the optimization problem solution. The above optimization method can be analytically described through relations (10) and (11):

$$v_i(t+1) = w \cdot v_i(t) + C_1 \cdot r_1 \cdot (p_{besti}(t) - x_i(t)) + C_2 \cdot r_2 \cdot (g_{best}(t) - x_i(t)) \qquad (10)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \qquad (11)$$

where: t – iteration ordinal number, x_i– location of i-th individual, $v_i -$ movement of i-th individual, w – inertia coefficient, $C_1, C_2 -$ acceleration coefficients, $r_1, r_2 -$ random numbers from the interval $[0,1]$.

When solving the above optimization problem, the individual is represented by a vector of control variables with 25 coordinates, the first of which is the location (the distribution network node index where the system is connected), and the other 24 coordinates are the mean one-hour powers of the observed system during the day. After each iteration, coordinates of the individuals are changed in order to reduce the value of their criterion function, which after the appropriate number of iterations (when the change in the criterion function of the best solution is negligible) gives the solution to the optimization problem. As part of the solution to the optimization problem, the optimal location of the system consisting of a PV system and an ESS was directly obtained, while the obtained optimal powers were used to determine the optimal system configuration.

3.2 Determining the optimal configuration of a system consisting of a PV system and an ESS

This paper adopts a configuration ensuring distribution network loss minimization with minimal sizing of the PV system and ESS, for the optimal configuration of a system consisting of a PV system and an ESS, whose principle diagram is shown in Figure 1.

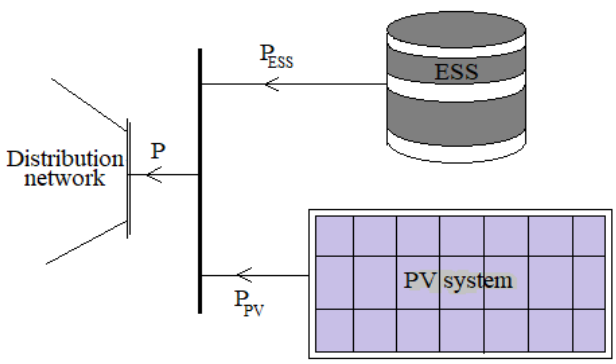


Figure 1. A principal diagram of a system consisting of a PV system and an ESS

To determine the optimal configuration, the obtained optimal power was used, which the mentioned system should inject into the distribution network during the day in order to minimize pertaining losses, as well as the daily solar irradiation diagram of the PV system. In the applied approach, the first step in determining the optimal configuration of a system consisting of a PV system and an ESS is sizing the PV system, i.e. determining its maximum power. To make this possible, it is necessary to express the PV system power for each hour of the day in terms of its maximum power (P_{PVmax}) and solar irradiation during the day:

$$P_{PV}(h) = P_{PVmax}\frac{I_C(h)}{I_{Cmax}} \tag{12}$$

where $P_{PV}(h)$ and $I_C(h)$ are power and solar irradiation of the PV system in the h-th hour, while I_{Cmax} is the maximum solar irradiation of the PV system during the day. The power of the PV system follows the daily solar irradiation diagram of its panels, which is the reason why this system is often unable to meet the required optimal power by itself. To solve this problem, an ESS was used, which, according to needs, can play the role of consumption (charging period) or generation (discharging period), and ensures that the power injected into the distribution network is equal to the optimal power (P_{opt}).

$$P_{ESS} = P_{opt} - P_{PV} \tag{13}$$

Considering that in this paper mean one-hour powers are used, the state of charge of the ESS at the end of the k-th hour, during charging and discharging can be determined from relations (14) and (15) respectively:

$$SOC_k = SOC_{k-1} - \frac{\eta}{Q_{ESS}}P_{ESS}(k) \tag{14}$$

$$SOC_k = SOC_{k-1} - \frac{1}{\eta\cdot Q_{ESS}}P_{ESS}(k) \tag{15}$$

where: SOC_k – ESS state of charge at the end of the k-th hour, SOC_{k-1} – ESS state of charge at the end of the k-1-th hour, $P_{ESS}(k)$ – mean one-hour power of the ESS in the k-th hour (with a value less than zero during the charging time and greater than zero during the discharge), Q_{ESS} – total, computational energy capacity of ESS, η – efficiency level of the ESS charging and discharging process.

By using the expression (12) in (13) and then expression (13) in (14) and (15), the difference between the ESS state of charge at the end and the beginning of the observed period (ΔSOC) can be determined as:

$$\Delta SOC = \sum_j^m\left(P_{PVmax}\frac{I_C(j)}{I_{Cmax}} - P_{opt}(j)\right)\frac{\eta}{Q_{ESS}} - \sum_i^n(P_{opt}(i) - P_{PVmax}\frac{I_C(i)}{I_{Cmax}})\frac{1}{\eta\cdot Q_{ESS}} \tag{16}$$

where i is the ordinal number of hours, while n is the total number of hours when the ESS is discharged, while j is the ordinal number of hours, with m being the total number of hours when the ESS is charged throughout the observed operating cycle.

The ESS charging periods occur when the required optimal power of the system composed of the PV system and ESS is lower, and the discharge periods when it is greater than the power of the PV system. Since the maximum power of the PV system is not known in advance, these periods must be assumed by looking at the shape of the optimal power and the solar irradiation diagrams. Using the assumed values for the charge and discharge periods, for a given efficiency level and zero difference between the state of charge of the ESS at the end and the beginning, the maximum power of the PV system based on expression (16) is:

$$P_{PVmax} = \frac{\sum_j^m P_{opt}(j)\eta + \sum_i^n P_{opt}(i)\frac{1}{\eta}}{\sum_j^m \frac{I_C(j)}{I_{Cmax}}\cdot\eta + \sum_i^n \frac{I_C(i)}{I_{Cmax}}\cdot\frac{1}{\eta}} \qquad (17)$$

After determining the maximum power of the PV system using expression (17), it is necessary to check the accuracy of the assumption made about the ESS charging and discharging periods. This is done by comparing the optimal power of the system composed of the PV system and the ESS with the power of the PV system determined from its maximum power using expression (12). If it turns out that the assumption is not correct, the procedure needs to be repeated by using new, better estimated charging and discharging periods. It should be noted that if the ESS efficiency level is equal to one, the situation is much simpler because it is not necessary to assume charging and discharging periods, so the maximum power of the PV system is obtained directly.

When the maximum power of the PV system is known, by using the expressions (12) and (13) it is possible to determine the power of the ESS for each hour of the observed period. The highest one-hour power of the ESS by absolute value during the operation period (T) is the power according to which it is necessary to size the ESS:

$$P_{ESSmax} = \max\{|P_{ESS}(k)|\},\ k = \{1,2,\ldots T\} \quad (18)$$

Subsequently, using expressions (14) and (15), the ESS states of charge are determined at the end of each hour inside the observed operation period. On the basis of the obtained values for the ESS states of charge, its sizing has been carried out, i.e. the required energy capacity determined. Minimum required energy capacity (ΔQ_{ESS}) which would enable the specified ESS operation is determined by using the expression (19):

$$\Delta Q_{ESS} = Q_{ESS} \cdot (SOC_{Max} - SOC_{Min}) \qquad (19)$$

where SOC_{Max} and SOC_{Min} are maximum and minimum states of charge of the ESS within the observed operation cycle.

In addition to the required energy capacity of the ESS, in order to achieve the desired (optimal from the network loss reduction aspect) operating mode, it is necessary to determine the permissible range in which the initial ESS state of charge can be found, so that the state of charge during the day is within the permissible values. The maximum and minimum values of ESS state of charge during the operation can be expressed using the initial state of charge of ESS and the charge/discharge power (P'_{ESS}) as:

$$SOC_{Max} = SOC_0 - \frac{1}{Q_{ESS}}\sum_{k=1}^{kmax} P'_{ESS}(k) \quad (20)$$

$$SOC_{Min} = SOC_0 - \frac{1}{Q_{ESS}}\sum_{k=1}^{kmin} P'_{ESS}(k) \quad (21)$$

where k_{min} and k_{max} are ordinal number of hours in which the minimum and maximum ESS state of charge occurs, while in the charging time power P'_{ESS} is considered to be $P'_{ESS} = \eta P_{ESS}$, and during discharge time $P'_{ESS} = P_{ESS}/\eta$.

The minimum and maximum charge levels occurring in the ESS operation must be within the permissible limits ($SOC_{Max} \leq SOC_{max}$ i $SOC_{Min} \geq SOC_{min}$), so the allowed range in which the initial ESS state of charge can be found, is obtained using expression (22):

$$SOC_{min} + \frac{1}{Q_{ESS}}\sum_{k=1}^{kmin} P'_{ESS}(k) \leq SOC_0 \leq SOC_{max} + \frac{1}{Q_{ESS}}\sum_{k=1}^{kmax} P'_{ESS}(k) \qquad (22)$$

4. DISCREPANCY BETWEEN ACTUAL AND EXPECTED VALUES OF LOAD AND SOLAR IRRADIATION

As can be seen in chapter 3, the presented method uses the expected load diagram of the distribution network to determine the optimal power that system consisting of a PV system and an ESS should inject into the network. Similarly, when determining the optimal system configuration, the method requires the knowledge of the shape of daily solar irradiation diagram of the PV system for the case of a clear day. Considering the above, it is clear that the system configuration optimality, and thus the distribution network loss reduction, largely depends on the forecast accuracy of the load diagram of the distribution network and solar irradiation diagram of the PV system. As can be assumed, three different cases are possible:

1. discrepancy between the actual and forecasted load diagram,
2. discrepancy between the actual and forecast solar irradiation diagram of the PV system,
3. discrepancy between actual and forecasted values of both considered diagrams.

In order to quantify the impact of the discrepancy between the actual and expected values of load and solar irradiation on the network loss increase, within each of the three examples, cases are considered where there is a change of the hourly characteristics compared to those predicted by the expected load diagram and the solar irradiation diagram of the PV system for the case of a clear day.

Depending on the method applied to solve the mentioned problem, two approaches were considered. In both approaches, in order to maximize the use of solar energy, it was assumed that the PV system operates with the maximum possible power at a given moment, which is directly proportional to the intensity of solar irradiation on its panels. On the other hand, the way to determine the ESS power depends on the approach used. Namely, in the first approach, the equality of the ESS state of charge at the beginning and at the end of the operating cycle must be preserved, while in the second approach this is not the case and only priority is network loss minimization. Therefore, the power of the ESS in the first approach (P_{ESS}^{I}) is equal to the ESS power obtained in the system configuration process (P_{ESS}), where the condition of equality of the ESS state of charge at the beginning and end of the operation cycle was satisfied.

$$P_{ESS}^{I} = P_{ESS} \tag{23}$$

Bearing in mind that the PV system power depends on the solar irradiation, which cannot be influenced, and that the ESS power is predetermined, the injected power of the system consisting of PV system and ESS in the first approach may greatly differ from the optimal value, which could result in a significant network loss increase. This can especially be pronounced in periods with higher cloud cover and higher load than expected, when the PV system power is only sufficient to provide an adequate supplement to the ESS.

Unlike the first, in the second approach, the load is measured and based on this information PSO determines the optimal power that system should inject into the network at a given moment in order to minimize losses. The power of the ESS in second approach (P_{ESS}^{II}) is adjusted so that at all times, regardless of the current PV system power (P_{PV}), in the network is injected optimal power needed for the loss minimization perspective (P_{opt}).

$$P_{ESS}^{II} = P_{opt} - P_{PV} \tag{24}$$

It is clear that this approach successfully minimizes the network losses, but can also lead to a large difference between the ESS state of charge at the end and at the beginning of the operating period, which is the reason why the use of this approach is limited to special situations. It should be noted that regardless of the used approach, the constraints in the form of required maximum power (P_{ESSmax}) and the required ESS energy capacity (ΔQ_{ESS}), obtained in the system configuration process, must be satisfied. These constraints for the k-th hour are given by expressions (25) and (26), respectively:

$$P_{ESS}^{I,II}(k) < P_{ESSmax} \tag{25}$$

$$P_{ESS}^{I,II}(k) < \Delta Q_{ESS} - \sum_{i}^{k-1} P_{ESS}^{I,II}(i) \tag{26}$$

5. PRESENTATION AND ANALYSIS OF THE RESULTS

All the results obtained in this paper refer to the IEEE radial distribution network with 33 nodes, shown in Figure 2. The same distance between every two adjacent nodes has been adopted and it is 250 m. This was done for the sake of simplicity in drawing general conclusions. The distribution network voltage level is 10 kV, while the values of longitudinal active resistance and reactance are r =0.414 Ω/km and x =0.365 Ω/km.

The PSO was implemented to obtaine the optimal solution after 100 iterations using a population of 200 individuals. Based on a large number of performed simulations, the values of inertia coefficient and the acceleration coefficients that gave the best results are adopted, and they are: $w = 0.85$, $C_1 = 0.5$ i $C_2 = 0.6$.

Three different distribution network load diagrams are considered, shown in Figures 3, 4 and 5. The shapes of the first two load diagrams have a more theoretical character and are chosen as examples of loads that more or less matches the daily solar irradiation diagram of the PV system. As can be seen from Figures 3 and 4, the first and second distribution network load diagrams have different distributions of load power in time, but the same maximum ($P_{max1,2} = 4.462MW$) and mean power ($P_{av1,2} = 3.285MW$). Unlike them, the shape of the third load diagram, shown in Figure 5, better describes the load that can be found in practice and has a slightly higher maximum ($P_{max3} = 4.75MW$) and mean power ($P_{sr3} = 3.398MW$). In all considered cases, a uniform load distribution was used across the distribution network nodes. Also, for each load diagram, two different types of load are considered, the constant power load type (industrial load), and the constant impedance load type (resistive load), where for the indicated distribution network voltage (10 kV) active powers of both load types are the same and equal to those on the load diagram.

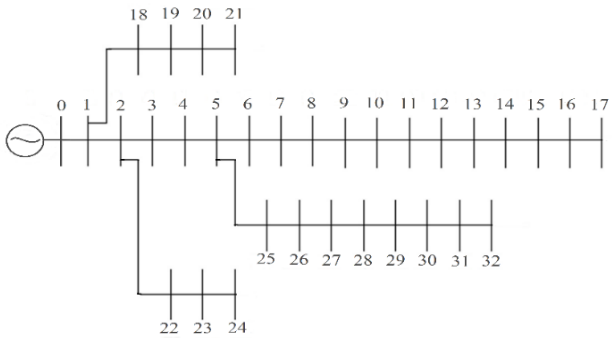


Figure 2. IEEE 33 distribution network

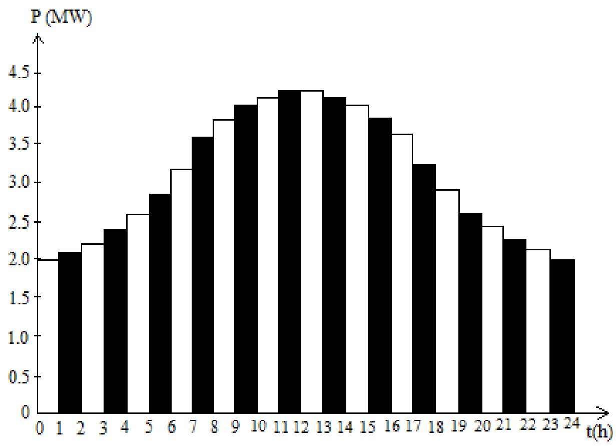


Figure 3. The first distribution network load diagram

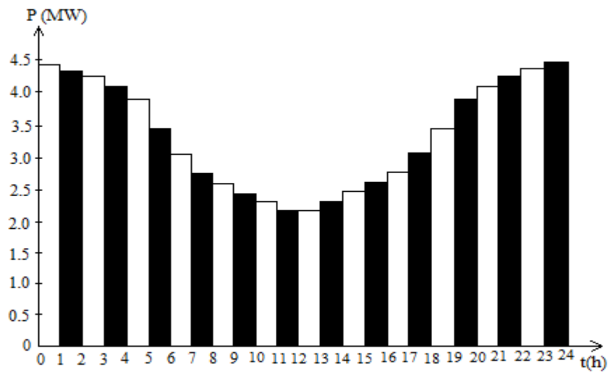


Figure 4. The second distribution network load diagram

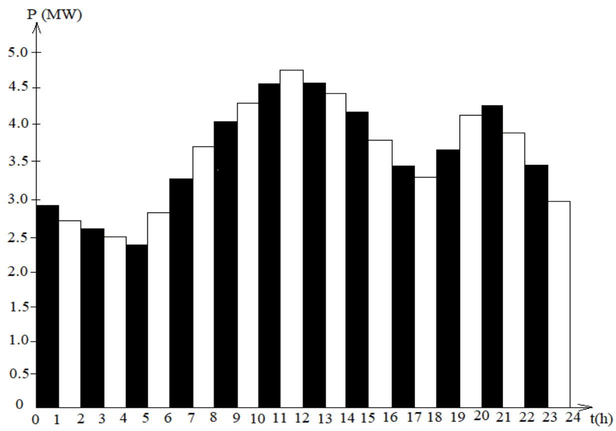


Figure 5. The third distribution network load diagram

It is important to note that in each considered case the time distribution of the load of each node is the same and follows the used load diagram of the distribution network. Likewise, the load power factor is the same throughout the day and uniform along the entire distribution network, while its value is $cos\varphi = 1$ and $cos\varphi = 0.89$ for resistive and industrial type loads, respectively.

The daily solar irradiation diagram of the PV system, used in determining the PV system power, expressed per unit, is given in Figure 6.

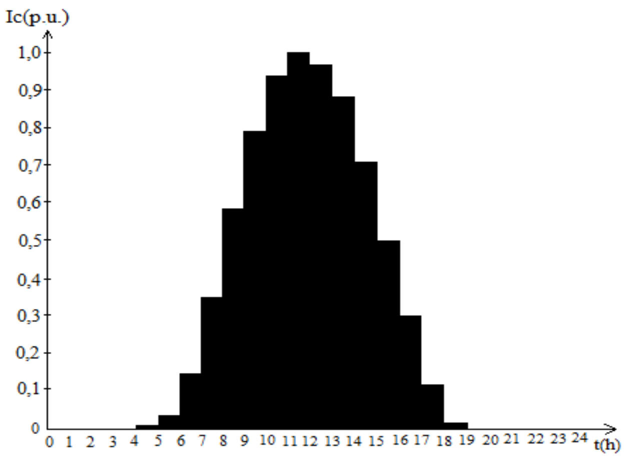


Figure 6. Daily PV system solar irradiation diagram

Table I shows the values of the mean daily power of losses in the distribution network before the system consisting of the PV system and the ESS has been connected, for all three load diagrams, where the values in brackets refer to the constant impedance load type, and the values without brackets to the constant power load type.

Table I. Mean daily power of losses before the system consisting of PV system and ESS has been connected

Load diagram	I	II	III
$P_{loss}[kW]$	63.037 (46.001)	63.037 (46.001)	68.097 (49.498)

Results in Table I are expected, given that the powers of the first and second load diagrams, although distributed differently in time, are the same in terms of values and slightly less than in the case of the third load diagram. Furthermore, the fact that the network nodes voltages are slightly lower than indicated, as well as the existence of reactive power flows in the network in the case of a constant power load, results in higher losses for such load type.

Considering the obtained optimal locations and power of the system consisting of PV system and ESS, Table II contains the results after it was connected to the distribution network. These results, in addition to the mean daily power of losses (P_{loss}), contain the optimal location (distribution network node index) where the system is connected (i), as well as the required maximum power of the PV system (P_{PVmax}), required maximum power of the ESS (P_{ESS}) and the required energy capacity of the ESS (ΔQ_{ESS}) for different levels of ESS efficiency (η=1, η=0.9 i η=0.8). It should be noted that in the presented procedure, the ESS efficiency level does not affect the location and power of the system consisting of PV system and ESS, only its configuration (maximum power of the PV system, maximum power and energy capacity of the ESS).

Based on the results in Table II, it can be concluded that by connecting a system consisting of PV system and ESS, distribution network losses can be significantly reduced. As the mean power of losses after connection is the same for the first and second load diagram, and slightly higher in the third, it may be ascertained that the level of losses after connection is affected by the load power value, rather than its distribution in time. Moreover, Table 2 shows that the optimal location of the system consisting of the PV system and the ESS does not depend on the load diagram, and that for all three load diagrams, regardless of the load type, it is node 5. In addition, Table 2 shows that the maximum power of the PV system increases with the increase of the mean daily power of load, while the influence of the shape of the load diagram is greater if the

ESS efficiency is lower (it does not exist for unit efficiency). For the energy capacity and maximum power of the ESS, the matching between the load diagram and the power generation diagram of the PV system is of the greatest importance, which is shown by a much higher energy capacity and maximum power of the ESS in the case of the second than in the case of the first load diagram. Also, the maximum power of the PV system and the required energy capacity and the maximum power of the ESS increase while the ESS efficiency decreases. This results from the fact that for the same injected power, more ESS discharge power is needed, and that for the same ESS charging power, more power coming from the PV system is needed, if a reduction in ESS efficiency occurs. The above observations are valid for both load types, whereby the slightly higher values of the maximum power of the PV system and ESS, as well as the energy capacity of the ESS, in the case of a constant power load type is the result of a slightly higher load in that case.

Table II. Mean daily power of losses after system consisting of PV system and ESS has been connected, connection location and system configuration parameters for different levels of ESS efficiency

Load diagram	I	II	III
$P_{loss}[kW]$	24.047 (11.257)	24.047 (11.257)	25.970 (12.125)
i	5 (5)	5 (5)	5 (5)
$P_{PVmax1}[MW]$	8.530 (8.354)	8.529 (8.354)	8.830 (8.640)
$P_{ESS1}[MW]$	4.988 (4.905)	6.855 (6.702)	5.056 (4.972)
$\Delta Q_{ESS1}[MWh]$	27.115 (26.680)	40.783 (39.827)	29.219 (28.701)
$P_{PVmax0,9}[MW]$	9.382 (9.192)	9.825 (9.619)	9.758 (9.551)
$P_{ESS0,9}[MW]$	5.841 (5.744)	8.154 (7.968)	5.984 (5.884)
$\Delta Q_{ESS0,9}[MWh]$	29.508 (29.045)	44.861 (43.817)	32.131 (31.554)
$P_{PVmax0,8}[MW]$	10.522 (10.316)	11.594 (11.347)	11.026 (10.796)
$P_{ESS0,8}[MW]$	6.981 (6.867)	9.923 (9.695)	7.252 (7.128)
$\Delta Q_{ESS0,8}[MWh]$	32.370 (31.872)	49.784 (48.624)	35.657 (35.017)

Figures 7 and 8 show the mean daily power of losses along the distribution network sections before and after the connection of the system consisting of PV system and ESS, for both considered load types that follow the third load diagram. The indexes (ordinal numbers) of the sections are equal to the node indexes at their ends.

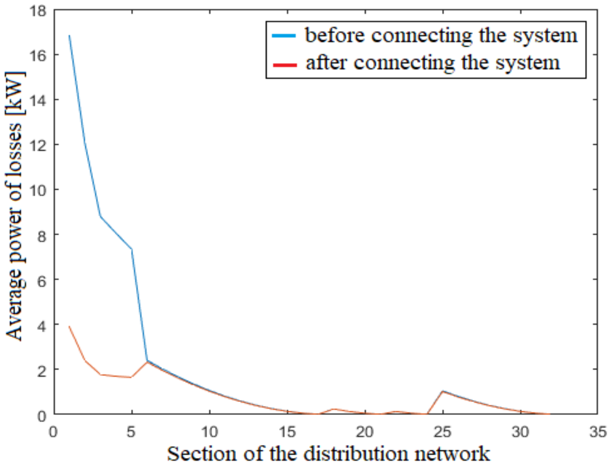


Figure 7. Mean daily power of losses along the distribution network sections for constant power load

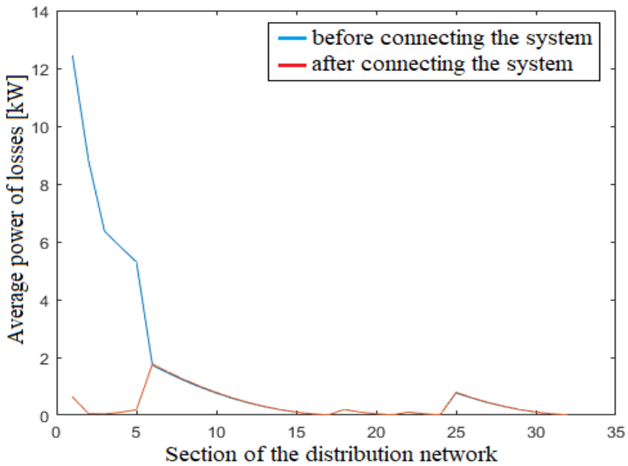


Figure 8. Mean daily power of losses along the distribution network sections for constant impedance load

Figures 7 and 8 show that by connecting a single system consisting of PV system and ESS, the greatest reduction in losses is achieved in the supply sections of the distribution network where several of its branches branch off. Also, it can be observed that due to the existence of reactive power flows that could not be significantly influenced by connected system, the supply sections losses are higher in the case of a constant power load type.

Figures 9 and 10 show the active load power of the distribution network, the optimal (operating) power of the system consisting of PV system and ESS, as well as the power of PV system and ESS individually, for the ideal efficiency of the ESS and the third load diagram.

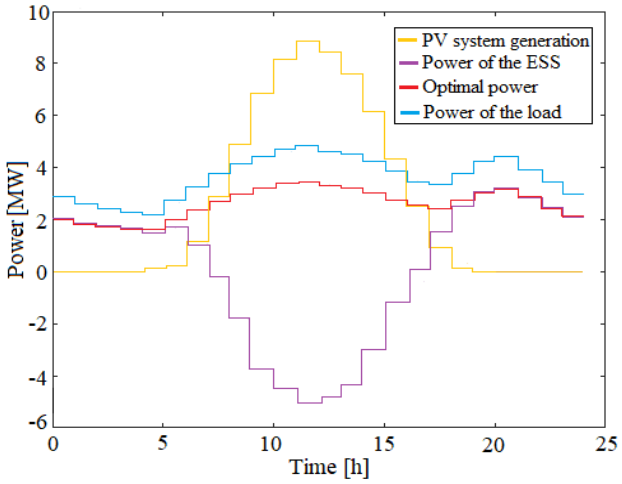


Figure 9. Active load power, optimal (operating) power of the system consisting of PV system and ESS, power of the PV system and power of the ESS, for constant power load type

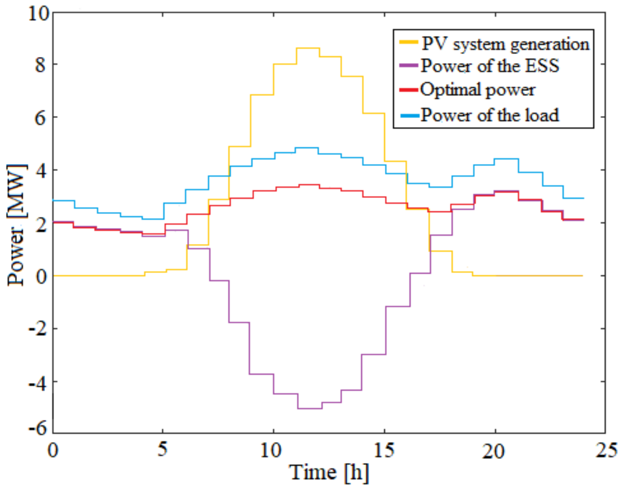


Figure 10. Active load power, optimal (operating) power of the system consisting of PV system and ESS, power of the PV system and power of the ESS, for constant impedance load type

Figures 9 and 10 show that the optimal (operating) power of the system consisting of PV system and ESS follows the shape of the load power, while in periods of high solar irradiation it is provided by the PV system, whereas at night and in periods with low solar irradiation it is generated by the ESS. As expected, in periods of high solar irradiation the ESS is charging, while in periods with low solar radiation it is discharging.

Table III shows the minimum mean daily power of losses, the mean daily power of losses obtained by the first and second approaches and the change in the ESS energy level obtained at the end of the operating cycle compared to that at the beginning using the second approach, for different discrepancies between the actual and expected values of load power and solar irradiation. It is important to note that the used load power deviation (ΔP) is the same percentage-wise for every hour during the day, which also applies to the solar irradiation deviation (ΔI_c). The minimum mean daily power of losses is obtained for the case when the system consisting of PV system and ESS injects optimal power every hour from the aspect of losses reduction, considering the real load value inside the network, and ignoring the constraints determined by the system configuration. This power of losses has a theoretical character and serves as a reference to evaluate the effectiveness of the first and second approach. The two mentioned approaches are explained in detail in the fourth chapter.

Table III. Minimum mean daily power of losses, mean daily power of losses in the first and second approach and the change in the ESS energy level obtained in the second approach, for different discrepancies between the actual and expected values for load power and solar irradiation.

$\Delta P(\%)$, $\Delta I_c(\%)$	$P_{loss,min}[kW]$	$P^{I}_{loss}[kW]$	$P^{II}_{loss}[kW]$	$\Delta W^{II}_{ESS}[MWh]$
30, 0	44,339 (20,414)	48,202 (23,564)	44,340 (20,414)	-19,365 (-18,949)
20, 0	37,651 (17,416)	39,355 (18,823)	37,652 (17,416)	-12,910 (-12,632)
10, 0	31,530 (14,653)	31,953 (15,006)	31,530 (14,653)	-6,454 (-6,316)
−10, 0	20,951 (9,837)	21,367 (10,190)	21,839 (10,625)	3,207 (3,154)
−20, 0	16,501 (7,780)	18,152 (9,214)	18,885 (9,904)	6,401 (6,290)
−30, 0	12,593 (5,963)	16,282 (9,206)	17,402 (10,284)	9,596 (9,426)
0, −10	25,970 (12,125)	26,921 (12,963)	25,970 (12,125)	-6,455 (-6,316)
0, −20	25,970 (12,125)	29,807 (15,505)	25,970 (12,125)	-12,910 (-12,632)
0, −30	25,970 (12,125)	34,674 (19,790)	25,970 (12,125)	-19,365 (-18,948)
30, −30	44,339 (20,414)	66,161 (38,681)	51,240 (26,270)	-29,219 (-28,701)
20, −30	37,651 (17,416)	54,174 (31,468)	39,322 (18,903)	-29,219 (-28,701)
10, −30	31,530 (14,653)	43,689 (25,167)	31,530 (14,653)	-25,819 (-25,264)
−30, −20	12,593 (5,963)	14,349 (7,565)	12,593 (5,963)	6,454 (6,316)
−30, −10	12,593 (5,963)	14,385 (7,545)	13,657 (6,911)	9,324 (9,159)
−20, −20	16,501 (7,780)	18,110 (9,255)	16,501 (7,780)	0 (0)

Based on the results in the Table III, it can be concluded that in most cases the losses obtained in the second approach are significantly lower than those obtained using the first approach. The difference between the losses obtained by the second approach and the minimum losses is a result of the constraints related to the maximum power and energy capacity of the ESS determined by the system configuration. Moreover, the results in Table 3 show that using the second approach ESS is recharged at the end of the day ($\Delta W_{ESS} > 0$) in the case when the load reduction is more significant than the solar irradiation reduction, while otherwise the energy of the ESS is lower at the end compared to the beginning of the day ($\Delta W_{ESS} < 0$). ESS discharge after the operating cycle is particularly pronounced when there is a load increase and a solar irradiation decrease compared to their expected values during the day.

By comparing the value of minimum average daily power of losses and the power of losses obtained using the first approach, it may be concluded that neglecting the deviations of the actual from the expected values of load and solar irradiation when determining the power of the PV system and the ESS leads to a network loss increase. On the other hand, large ESS discharges in the second approach indicate that consideration of the deviation and adjustment of the injection power into the network should not only be done at the expense of the ESS power, but also by increasing the powet of the PV system in the configuration phase.

6. CONCLUSION

This paper presents a methodology for determining the optimal location and configuration of a system consisting of PV system and ESS to reduce the distribution network losses. Obtained results showed that by connecting such a system, distribution network losses can be significantly reduced, regardless of the shape of the load diagram and its type, and that the optimal connection location is a node near the network centre (load). Furthermore, based on the results, it may be concluded that the greatest influence on the sizing of the PV system and its maximum power, has the mean daily load power, while the maximum power and energy capacity of the ESS mostly depend on the matching between the load diagram and the solar irradiation diagram of the PV system. By comparing the results for different levels of ESS efficiency, it is clear that the reduction of ESS efficiency leads to an increase in the maximum power of the PV system and the maximum power and energy capacity of ESS, for the same level of network losses reduction. Finally, it should be pointed out that the discrepancy between the actual and expected load power and the reduction of solar irradiation below the expected value can lead to an increase in network losses or to a great extent change the state of charge of the ESS.

REFERENCES

[1] Anaza O. S, Haruna S. Y, Amoo L. A, Sadiq A. A, Yisah A. Y, “Potential of renewable energy sources for distributed generations: An overview”, *International Journal of Scientific Advances*, Vol. 4, No. 1, pp. 107-117, 2023.

[2] Rajaković N, Tasić D., “Distributivne i industrijske mreže”, Akademska misao, Beograd, 2008.

[3] Alam A, Gupta A, Bindal P, Siddiqui A, Zaid M., “Power loss minimization in a radial distribution system with distributed generation”, *International Conference on Power, Energy, Control and Transmission Systems*, Chennai, India, pp. 21-25, 2018.

[4] Das C. K, Bass O, Kothapalli G, Mahmoud T.S, Habibi D, “Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality”, *Renewable and Sustainable Energy Reviews*, Vol. 91, pp. 1205–1230, 2018.

[5] Tang X, Deng K, Wu Q, Feng Y., “Optimal location and capacity of the distributed energy storage system in a distribution network”, *IEEE Access*, Vol. 8, pp. 15576-15585, 2020.

[6] Das S, Fosso O, Marafioti G., “Efficient distribution network loss minimization with optimal DG placement and operation”, *IEEE 12th Energy Conversion Congress and Exposition – Asia*, Singapore, 2021.

[7] Ortiz J, Kasmaei M, Lehtonen M, Mantovani J, “Optimal location-allocation of storage devices and renewable-based DG in distributed systems”, *Electric Power System Research*, Vol. 172, pp. 11-21, 2019.

[8] Adetunji K, Hofsajer I, Abu-Mahfouz A, Cheng L., “A review of metaheuristic techniques for optimal integration of electrical units in distribution network”, IEEE Access, Vol. 9, pp. 5046-5068, 2020.

[9] Mahesh K, AL Nallagownden P, AL Elamvazuthi I., “Optimal placement and sizing od DG in distribution system using accelerated PSO for power loss minimization”, *IEEE Conference on Energy Conversion*, Johor Bahru, Malaysia, 2015.

[10] Michline J, Ganesh S., “Power flow analysis for radial distribution system using backward/forward sweep method”, *International Journal of Electrical and Computer Engineering*, Vol. 8, No. 10, pp. 1628-1632, 2014.

[11] Wong L, Shareef H, Mohamed A, Ibrahim A., “Optimal placement and sizing of energy storage system in distributed network with photovoltaic based distributed generation using improved firefly algorithms”, *International Journal of Energy and Power Engineering*, Vol. 11, No. 9, pp. 895-903, 2017.

[12] Radosavljević J., “Metaheuristic optimization in power engineering”, Institution of Engineering and Technology, London, 2018.

[13] Elattar E. E, Elsayed S.K, “Optimal location and sizing of distributed generators based on renewable energy sources using modified moth flame optimization technique”, *IEEE Access*, Vol. 8, pp. 109625–109638, 2020.

[14] Das C. K, Bass O, Kothapalli G, Mahmoud T. S, Habibi D, "Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm", *Applied Energy*, Vol. 232, pp. 212–228, 2018.
[15] Goli P, Yelem S, Jasthi K, Gampa S. R, Das D, "Optimum placement of battery energy storage systems and solar PV units in distribution networks using gravitational search algorithm" *In: Proceedings of the International Conference on Artificial Intelligence Techniques for Electrical Engineering Systems (AITEES)*, pp. 113–123, 2022.
[16] Duong M. Q, Pham T. D, Nguyen T. T, Doan A. T, Tran H. V, "Determination of optimal location and sizing of solar photovoltaic distribution generation units in radial distribution systems", *Energies*, Vol. 12, No. 1, pp. 174 2019.
[17] Mansouri N, Lashab A, Guerrero J. M, Cherif A, "Photovoltaic power plants in electrical distribution networks: a review on their impact and solutions", *IET Renewable Power Generation*, Vol. 14, No. 12, pp. 2114–2125, 2020.
[18] Parihar S. S, Malik N, "Possibilistic uncertainty assessment in the presence of optimally integrated solar PV-DG and probabilistic load model in distribution network", Facta Universitatis Series: Electronics and Energetics, Vol. 35, No.1, pp. 71-92, 2022.
[19] Wang J, Wang J, Guo J, Wang L, Zhang C, Liu B, "Research progress of complex network modeling methods based on uncertainty theory", *Mathematics*, Vol.11, No. 5, 1212, 2023.

BIOGRAPHIES

Nikola Krstić was born on 24 February 1995 in Niš. He graduated in 2018 and completed his master's academic studies in 2019 at the Faculty of Electronics in Niš.

His main areas of interest include distribution network analysis, power systems optimization using metaheuristic optimization methods, and photovoltaic systems.
He is currently a doctoral student and works as an assistant at the Department of Energy at the Faculty of Electronics in Niš.

Dragan Tasić was born on 22 September 1961 in Guberevac, Leskovac municipality. He graduated in 1986 at the Faculty of Electrical Engineering in Belgrade, and received his doctorate in 1997 at the Faculty of Electronics in Niš. His main areas of interest include power system analysis, power cable engineering and power industry optimization methods.
He is a full professor at the Department of Energy at the Faculty of Electronics in Niš.

UDK: 621.383.51
621.316

Nikola N. Krstić[1], Dragan S. Tasić[1]

Metoda za određivanje optimalne lokacije i konfiguracije sistema sačinjenog od fotonaponskog i sistema za skladištenje energije uzimajući u obzir smanjenje gubitaka u distributivnoj mreži

[1] Elektronski fakultet u Nišu, Niš, Srbija*

Kategorija rada: originalni naučno-istraživački članak

Ključne poruke

- Ovaj rad razmatra smanjenja gubitaka u distributivnoj mreži priključenjem sistema sačinjenog od fotonaponskog (PV) i sistema za skladištenje energije (ESS).
- Određena je optimalna lokacija i optimalna snaga sistema sačinjenog od PV sistema i ESS uvažavajući minimizaciju gubitaka.
- Izvršeno je dimenzionisanje PV sistema i ESS.
- Sagledan je uticaj nepoklapanja stvarnih i očekivanih vrednosti opterećenja i sunčeve iradijacije na povećanje gubitaka u mreži i promenu nivoa napunjenosti ESS.

Kratak sadržaj

U ovom radu je predstavljena dvostepena metoda za određivanje optimalne lokacije i konfiguracije sistema sačinjenog od PV sistema i ESS uzimajući u obzir smanjenje gubitaka u distributivnoj mreži. U prvom koraku je uvažavajući očekivani dnevni dijagram opterećenja distributivne mreže, a korišćenjem metaheurističke optimizacione metode roja čestica (PSO), određena optimalna lokacija i optimalna snaga u toku dana sistema sačinjenog od PV sistema i ESS kako bi se minimizovali gubici u distributivnoj mreži. U drugom koraku procedure, određene su pojedinačne snage PV sistema i ESS i izvršena je njihova konfiguracija (dimenzionisanje). Ovo je urađeno iterativnim postupkom koristeći vrednosti optimalne zbirne snage ova dva sistema u toku dana dobijene u prvom koraku i oblika dnevnog dijagrama sunčeve iradiajacije PV sistema u slučaju vedrog dana. Postupak konfiguracije je detaljno objašnjen, a u okviru njega je određena potrebna maksimalna snaga PV sistema, maksimalna snaga ESS kao i energetski kapacitet ESS. Takođe, sagledan je uticaj odstupanja stvarnog od očekivanog dijagrama opterećenja kao i smanjenje sunčeve iradijacije u toku dana na povećanje gubitaka u distributivnoj mreži i promenu nivoa napunjenosti ESS. U radu su razmatrani slučaji sa različitim dijagramima opterećenja i različitim stepenima efikasnosti ESS. Svi rezultati su dobijeni korišćenjem IEEE radijalne distributivne mreže sa 33 čvora.

Ključne reči

Fotonaponski (PV) sistem, sistem za skladištenje energije (ESS), optimizaciona metoda roja čestica (PSO), gubici u distributivnoj mreži

Primljeno: 5. april 2023. Recenzirano: 25. april 2023.
Izmenjeno: 28. april 2023. Odobreno: 4. maj 2023.

*Korespondirajući autor: Nikola N. Krstić
E - mail: nikola.krstic@elfak.ni.ac.rs

Napomena:
Članak predstavlja proširenu, unapređenu i dodatno recenziranu verziju rada „*Optimalna lokacija i konfiguracija sistema sačinjenog od fotonaponskog i sistema za skladištenje energije uzimajući u obzir smanjenje gubitaka u distributivnoj mreži*“, nagrađenog u Stručnoj komisiji STK-4 *Distribuirana proizvodnja i efikasno korišćenje električne energije*, na 13. Savetovanju CIRED Srbija, Kopaonik, 12-16. septembra

UDC: 621.131.1:502.131.1(497.11)
620.9:339.13(497.11)

Dunja S. Grujić[1], Miloš M. Kuzman[2]

The Role of Aggregators in the Electricity Market Development

[1] Elektrodistribucija Srbije d.o.o. Beograd, Belgrade, Republic of Serbia*
[2] Serbian Energy Law Association, Belgrade, Republic of Serbia

Category of article: Review article

Highlights

- Aggregators as a new market participant
- A significant factor of green transaction - aggregator
- Efficient optimization of electricity production and consumption
- Impact on the flexibility of the power system

Abstract

In recent years, there has been an accelerated transition of the distribution power system from predominantly passive to active, primarily due to a rise in the number of electricity producers from renewable sources connected to the distribution system. In addition, amendments to the Law on Energy determined new users of the distribution system, including prosumers and electricity storage operators, whose mass connection to the distribution system is expected in the coming period. Aggregator has been recognized as an important new market participant, providing a service for the merging of electricity production and consumption in order to further sell, purchase or auction in the electricity market.

In this work, possible business models of aggregators, existing legal regulations and preconditions needed for their functioning on the market of the Republic of Serbia, shall be analyzed. Also, good international practices in this area will be presented in the work. In addition, efficient ways of merging the production and consumption of electricity, including final customers and producers, by aggregators, will be discussed.

The impact of the aggregators on the operations of the distribution system operator will be discussed, with a number of challenges ahead. Some of these challenges are related to system management and changes in power flows due to the connection of a significant number of new system users. At the end of the paper, an example will be presented that illustrates the possibility of aggregator acting in order to increase the flexibility of the power system.

Keywords

Aggregators, Managing Electricity Production and Consumption,

Energy Efficiency, Renewable Electricity Sources

Note:
This article represents an expanded, improved and additionally peer-reviewed version of the paper "*Models of the Functioning of Aggregators in the Electricity Market*", awarded by EC-6 *Electricity market and deregulation* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

Received: April 7th, 2023 Reviewed: May 22nd, 2023
Modified: May 26th, 2023 Accepted: May 27th, 2023
*Corresponding author: Dunja S. Grujić
Phone: +381-64-897-46-59 E - mail: dunja.grujic@ods.rs

1. INTRODUCTION

Regardless of the development speed of: innovations in the energy sector, acceleration of energy transition, or finding of alternative ways of energy sources use, the fact is that electrical energy (hereinafter: EE) is produced and consumed every day. In this process, we have producers on one side, and EE consumers on the other. Both strive to optimize the production and consumption of EE in such a way that it is more efficiently produced and consumed with lower marginal costs. Where it is technically and regulatory possible, and economically profitable, the key is in their cooperation for the sake of achieving a common goal, and this is where aggregators enter the scene.

The traditional division of EE producers on the one hand and EE consumers on the other, has shown shortcomings in practice, due to the fact that the supply and demand for EE on the market can never match perfectly, which shows that in certain periods during the calendar year there are significant deviations between the EE that is produced and the one which is consumed at a given moment. There are numerous reasons for this discrepancy, such as, for example, lack of EE from hydropower plants in the middle of droughts, increased consumption of EE in the winter months, a larger amount of EE entering the system from wind power plants during the night in a period when consumption is reduced, etc. Aggregation tends to achieve the optimization of the aforementioned inconsistencies and therefore it can represent a significant factor in the stability of the distribution system itself (hereinafter: DS) and the transmission system (hereinafter: TS). Aggregators have a positive impact on increasing the flexibility of DS and TS. Therefore, an example is given in the paper that shows the possibilities available to the aggregator to increase these flexibilities.

An essential prerequisite for the formation and development of aggregators and aggregating itself is the existence of appropriate legal regulations in this area. Since in the Republic of Serbia the aforementioned regulation has not been fully completed yet, this paper represents an opportunity to point out the existing legal framework, as well as the solutions that the regulation that should be adopted could contain, as well as business models of aggregators, including different ways of merging the production and consumption of EE, which in the author's opinion would represent the optimal solution in the existing market conditions. Furthermore, this paper will present one regional experience in this area.

The start of operation of the first aggregators in the Republic of Serbia will also be a challenge for the DS operator (hereinafter: DSO). In order to ensure the optimal management of DS, the DSO should, relying among other things on the missing regulation in this area, be able to control the operation of the aggregator at any time due to specific technical properties, such as for example the change of power flows due to the access of the aggregator to DS, i.e. producers and consumers whose production and consumption are aggregated by the aggregator. Therefore, this paper will pay special attention to the impact of aggregators on the operations of DSO.

2. CHALLENGES FACED BY DSO DUE TO THE CONNECTION OF NEW USERS TO DS

2.1 New users of DS

Environmental pollution, accelerated climate changes, as well as limited fossil fuel resources have led to an increase in global awareness of the need to produce EE from renewable sources, save electricity (as well as all other types) of energy, and increase energy efficiency.

In the Republic of Serbia, as well as in other countries of Europe and the world, production facilities for the production of EE from renewable sources, primarily from biomass, sun and wind, are being intensively built. Furthermore, a significant number of end customers decide to build their own renewable energy sources production facilities that they will connect to their internal installations, where they will use the produced EE for their own needs, and deliver the surplus to DS, thereby acquiring the status of prosumer [1,2,3]. The Republic of Serbia encourages the use of renewable energy sources in various ways (such as feed-in tariffs and auctions [2] for producers, while prosumers are offered, among other things, state subsidies [4], as well as a calculation model through net measurement, i.e. net calculation [2,3].

As an important DS user and market participant, an energy storage operator [1] is also recognized, who in periods when he has available EE surplus, would store it, so that it would be used when needed. The possibility of installing a storage is also given to prosumers [2,3].

In addition to changes in the behaviour of all EE end customers, caused by changes in lifestyles, modernization of numerous processes, as well as conditions on the EE market, the transportation sector should be especially taken into account. This sector is in a transition period, due to the need to preserve the environment, reduce exhaust gas emissions, and slow down climate change. The aforementioned circumstances affect the increasing number of electric and hybrid vehicles (hereinafter: e-vehicles) on the roads of the Republic of Serbia. In order to increase their number in the future, it is necessary to develop the adequate infrastructure, in terms of building a sufficient number of public charging stations whose consumption is extremely unpredictable. In addition to the above, we should take into account the advantage of using batteries for e-vehicles, which can represent potential mobile storage of EE [5].

Considering all of the above, DS becomes a dynamic, active system in which power flows are less and less predictable due to the connection of new, and changes in the operation of existing DS users with different roles in the newly emerging market conditions. As a result of the above, DSO faces challenges in DS management, voltage regulation, increased technical and non-technical losses, increase in DS load, reduction in capacity for connection of new DS users, congestion in DS, injection of EE from DS to TS, as well as the need for significant investments in DS in order to enable stable, reliable and safe operation of DS. All of the above leads to the need for better DS flexibility, which is also provided for in the Directive on common rules for the internal market of EE [6].

2.2 The flexibility of DS

Better flexibility of DS can be achieved in various ways. First of all, the DSO itself can reconfigure DS in order to increase flexibility. One of the ways to increase flexibility is to change the power source for individual users of DS due to the connection of a new production facility in order to use the produced EE more efficiently and put less burden on DS. Furthermore, a suitable choice of DS user connection point can be an additional source of flexibility, such as, for example, connection of production facilities at locations with a high load, in order to avoid their connection at low load DS locations, which may lead to new problems in DS management.

In addition to the above, users of DS can also increase the flexibility of DESS. With the development of the EE market, DS users can change their habits due to the fluctuation of the EE prices. Average hourly EE prices by month in 2021 from the Hungarian power exchange HUPX[1] are given in Figure 1 [7]. It can be noticed that the hourly price curve follows the DS hourly load curve, which is given in Figure 2 [8], and that in periods of higher load, DS and EE prices are higher and vice versa. If the suppliers were to sell EE to end customers at dynamic prices that would follow the described trends (different prices per hour, part of the day or similar), DS users, in order to reduce their costs for EE, would naturally reduce their consumption in the parts of the day in which DS is loaded (higher prices) and postpone their consumption for periods of less load on DS (periods of lower prices), thus contributing to the flexibility of DS.

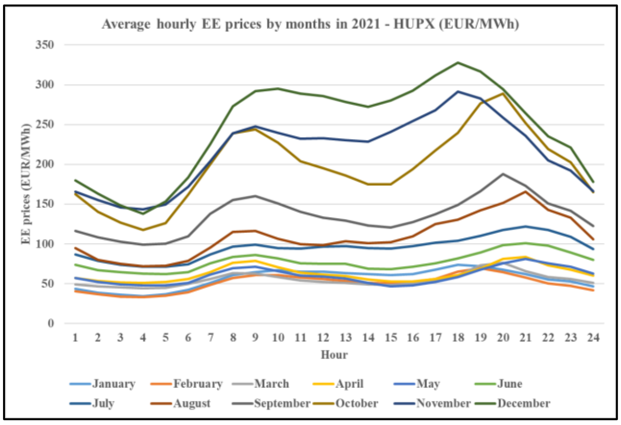


Figure 1. Average hourly EE prices by months in 2021 - HUPX stock exchange (EUR/MWh) [7]

In order to increase the described effect, DS access tariffs may become more dynamic in the future. By redefining tariffs through amendments [9] end customers (including charging stations for e-vehicles), prosumers, energy storage operators etc. would be motivated not to take over EE from DS in periods when DS is heavily loaded, but in periods of lower load. The current tariff concept with a daytime tariff lasting 16 hours and a night tariff lasting 8 hours does not achieve the desired effect completely, and the proposal is to determine at least four different tariffs that will reflect the objective situation in DS. The most expensive tariff would be in the period from 17:00 to 21:00, and the cheapest in the period from 00:00 to 08:00. (see Figure 2) [5]. Also, the modelling of special tariffs for producers and energy storage operators through amendments [9] is suggested which will stimulate energy storage operators and producers to deliver EE to DS in periods of the day when DS is loaded, i.e. to reduce or suspend deliveries in periods of less load. With the described changes, DS users would be encouraged to adjust their consumption and production independently, caused only by price signals, to the situation in DS, which would help the operations of DSO.

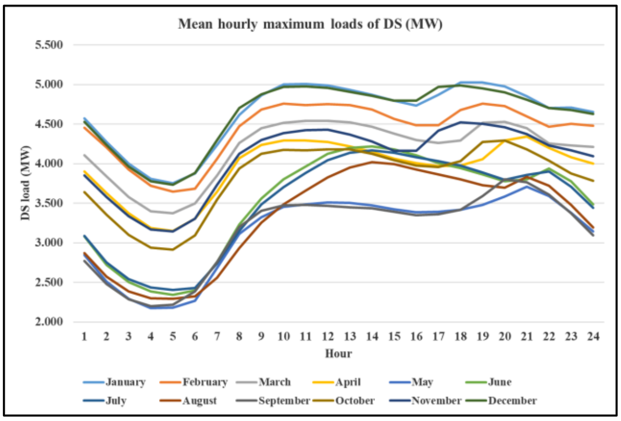


Figure 2. Mean hourly maximum loads of DS by month in 2021 (MW) [8]

In addition to the above, DSO is encouraged to explicitly procure flexibility services in transparent, non-discriminatory and market-based procurement procedures [6] in order to encourage operations and development of DSO. In view of the above, DSO may in the future conclude special contracts with DS users that would define the relationship between DS users and DSO in terms of increasing the flexibility of DS. DSO would issue orders to the users with whom it has concluded a contract, the implementation of which would facilitate DSO's operations, and the DS user would receive appropriate financial compensation. Also, in the coming period, the DSO may give DS users who want to participate in increasing the flexibility of DS various privileges in terms of reducing the costs of connection to DS, priority access to DS and the like.

DS users, motivated primarily by financial savings and additional income, but environmental protection as well, are becoming active participants in the EE market, and thus will be interested in getting involved in increasing the flexibility of DS in some of the described ways. It is reasonable to expect that the described trend will continue in the future because there has been a sudden and significant increase in EE prices on the EE market, which do not tend to fall (see Figures 1 and 3). However, due to

[1] In this paper, EE prices on the HUPX exchange are used. In Figure 3 comparison of average monthly EE prices on the HUPX and SEEPEX exchanges from January 2020 to March 2022 is given. They are almost identical.

their relatively small capacities, DS users often cannot operate on their own in the EE market. This is the reason why the aggregator [1,6] was recognized as a DS user and market participant.

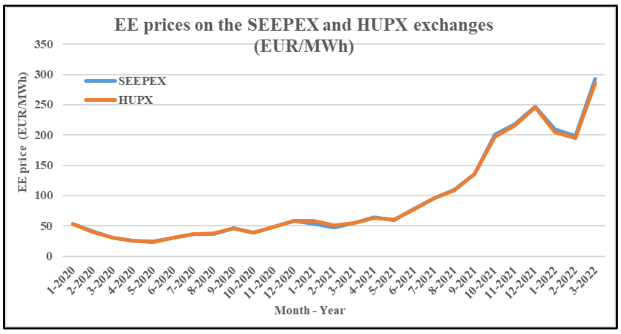


Figure 3. Average monthly EE prices (EUR/MWh); January 2020 – March 2022; SEEPEX and HUPX exchanges [7, 10]

3. REGULATION IN THE FIELD OF AGGREGATORS IN THE REPUBLIC OF SERBIA

Although the concept of aggregator is already widespread globally and is constantly developing [11], the Energy Law [1], with its amendments from April 2021, for the first time introduces the concept of aggregator into the legislation of the Republic of Serbia. Thus, in Article 2, paragraph 1, item 1a) of the Law, an aggregator is defined as a legal entity or natural person that provides the service of merging the consumption and/or production of EE for the purpose of resale, purchase or auctions on the EE markets, while in item 1) of the same paragraph, aggregating is defined as pooling consumption and/or production of EE for purchase, sale or auctions on EE markets. The aforementioned legal definitions, stipulate that the aggregator can aggregate only consumption, or production of EE, and can combine both production and consumption. This actually means that the aggregator coordinates the consumption or production of market participants in accordance with the law, where e.g. prosumers, due to their nature, can coordinate both production and consumption.

The law recognizes the aggregator as both a user of the system and a participant in the EE market, which guarantees them a wide range of both rights and obligations arising from [1], primarily the right to access DS, the right to non-discriminatory treatment, etc. Article 195, paragraph 1, item 17 [1] stipulates the supplier's duty not to expose end customers who have concluded a contract with the aggregator to unreasonable costs or contractual restrictions. In this way, the legislator wanted to guarantee that EE end customers will not be imposed additional obligations in case they decide to cooperate with the aggregator apart from those they already have in accordance with the law, which indirectly ensured the free will of end customers in the EE market to aggregate their consumption.

In a slightly more detailed manner, the rights and obligations of the aggregator are determined in Article 210b [1]. Thus, it is prescribed that the aggregator acts on the EE market in the name and on behalf of the market participants for whom they perform the service of unifying consumption and/or production, thus giving the aggregator the role of an agent in accordance with the general rules of the Law on Contracts and Torts. This actually means that the legal consequences of actions undertaken by the aggregator on the EE market, within the limits of legal authority, directly affect the producer or consumer of EE who has concluded a contract with the aggregator. Therefore, the clauses that are related to agency from the current Law on Contracts and Torts should be applied to the aggregator, including the clause of transgressing the limits of authority, if they are not in conflict with the nature of the aggregator. Therefore, it is necessary for EE producers and/or consumers who decide to aggregate their production or consumption to familiarize themselves in detail with the legal consequences of the aggregator's actions, especially with regard to the responsibility they could possibly bear due to actions taken by the aggregator on their behalf and for their account.

The same article [1] further stipulates that the aggregator is obliged to: 1) treat the market participant in a non-discriminatory manner; 2) publish the general conditions of the offer for the conclusion of the contract, that is, to inform the market participant in a convenient way about the offered conditions; 3) provide all relevant data to the market participant free of charge at least once during the accounting period if the market participant requests it; and 4) to inform the market participant about the aggregation function on its website, or in another appropriate way. The aforementioned rules are only set in principle and their further development is expected, primarily through amendments to the valid Rules on the operation of the DS [12, 13] and Rules on the operation of the EE market. [14].

4. THE ROLE OF AGGREGATORS ON THE EE MARKET

Each user of the system, including the aggregator, is obliged to arrange access to the system to which he is connected, as well as balance responsibility. All users of the system independently arrange access to the system and balance responsibility, except for those who have concluded a supply agreement for the entire production of the EE with the supplier. In the described case, the supplier has the obligation to regulate access to the system and balance responsibility for the points of handover of the system users in question. System users who are part of an aggregated group, in addition to contracts regulating supply, access to the system and balance responsibility, conclude a separate contract on aggregation with the aggregator. Furthermore, the aggregator as a system user and market participant is obliged to regulate access to the system and balance responsibility. [1]

4.1 Relationship between DSO and aggregator

The main goal of DSO is that at any time there is enough EE in DS to meet the needs of all users of DS. In the realization of this goal the aggregator can play a key role in the future. As already stated, its role is to aggregate the consumption and production of several market participants with their different functions (end customers, producers, energy storage operators, prosumers, etc.) in order to complement each other and enable greater financial savings for the aggregated participants on market (hereinafter: aggregated group), profit to the aggregator, the supplier and the balance responsible party (hereinafter: BRP), but also enable greater flexibility of DS, which achieves the full effect of aggregation. The aggregator will receive financial compensation from the DSO, while the members of the aggregated group will receive financial compensation from the aggregator (direct financial compensation, or various privileges in terms of reduction of electricity bill, etc., depending on the conditions under which the aggregation contract was concluded).

In order to implement the orders of the DSO, examples of the aggregator's action on the members of the aggregated group will be given below. For the purposes of this paper, the case of an aggregated group in which final customers are aggregated will be analyzed (industrial final customers, public e-vehicle charging stations, households, final customers who own e-vehicles, etc.), producers from renewable sources, prosumers (with and without own storage) and energy storage operators.

In the event that DS is overloaded, DSO will issue an order to the aggregator, in accordance with the concluded contract, to provide the amount of *X* EE to DS. At the same time, the aggregator, in accordance with the aggregation contracts it has with the members of the aggregated group, can issue an order to:

- controllable production units to increase the production of EE by the amount of PRp;
- end customers (including public e-vehicle charging stations) to reduce consumption by the amount of KKp, compared to their initial plan, which will reduce the amount of required EE for the end customers in question;
- storages (if they are filled) to deliver an additional amount of EE Sp over the planned amount of EE for delivery to DS, that is, to reduce the offtake from DS for Ssp, compared to the plan;
- prosumers to increase the delivery of EE to DS (if at the given moment the production facility produces EE, i.e. from the battery if they have one) by the amount of KPIp, i.e. to reduce offtake from DS (to reduce consumption or to use EE from their own battery if they have one and if it is filled) for the amount of KPPp.

With all the described measures, acting of different market participants who are part of the aggregated group, through the aggregator, the total available EE in DS increases, in accordance with the request of DSO, by the amount *X*:

$$X = PRp + KKp + Sp + Ssp + KPIp + KPPp \quad (1)$$

There are also opposite situations, in which there is more EE in the DS than is needed at a given moment (e.g. during the night). The DSO issues an order to the aggregator, in accordance with the concluded contract, to reduce the total amount of available EE in the DS system by the amount Y. At the same time, the aggregator, in accordance with the aggregation contracts it has with the members of the aggregated group, can issue an order to:

- controllable production units to reduce EE production by the amount of PRs;
- end customers (including public e-vehicle charging stations) to increase EE consumption by the amount of KKs compared to their initial plan, which will increase the required EE for the end customers in question,
- storages to reduce the delivery of EE to DS by the amount of Ss compared to the plan, i.e. to increase the offtake from DS by Sss compared to the planned amounts,
- prosumers to reduce the delivery of EE to DS by the amount of KPIs (if at the given moment the production facility produces EE to increase the consumption of produced EE, i.e. to charge their batteries if possible), i.e. to increase the offtake from DS by the amount of KPPs (to increase consumption or to use EE from DS instead of its own battery if it is charged).

With all the described measures, the action of various market participants who are part of the aggregated group, through the aggregator, the total available EE in DS is reduced, in accordance with the requirement of DSO, by the amount Y:

$$Y = PRs + KKs + Ss + Sss + KPIs + KPPs \quad (2)$$

The aggregator determines, primarily on the basis of economic parameters and the aggregation contract, which of the listed resources it will engage in order to fulfil the order of the DSO. The effect of the aggregator is equivalent to one power plant that produced the amount of EE X at the required time in case it is necessary to increase the total available EE in DS, i.e. reduced its production by the amount of EE Y and thereby reduced the total available EE in DS by that amount. In view of the above, it can often be seen in the literature that aggregators are named as virtual power plants [15, 16, 17].

4.2 Business models of aggregators on the EE market

The supplier, which is also a BRP, or has transferred the balancing responsibility to another BRP, can also play the role of an aggregator. The practice of European countries so far has shown that suppliers are reluctant to take on the role of aggregators [18], because this affects the reduction of EE sales (especially in periods of high prices), which is their core activity, thereby reducing their own profits.

On the other hand, the aggregator can operate independently from the supplier, which is also the so-called BRP, independent aggregator [6]. By activating its mechanisms, an independent aggregator can cause additional costs to both the supplier (unsold purchased EE in a certain hour) and the BRP (imbalance in the observed hour). In such cases, compensation for unsold EE to the supplier and costs of BRP imbalance by market participants is provided, but only to the realistic extent caused by the action of the aggregator [6]. In [6] it is defined that the method of calculating the amount of the mentioned compensation is approved by the regulatory authority.

The third possibility is that the independent aggregator is BRP, independent from the supplier. This concept is initially more realistic, because in the case that there are no orders from the DSO, the aggregator can manage the participants in the market it aggregates in such a way as to contribute to the reduction of its own imbalance costs. Suppliers acquire EE to sell to end customers, prosumers, energy storage operators, etc., which they supply according to their EE needs plan. However, suppliers plan the amount of EE that they will buy from producers, prosumers, energy storage operators, etc. BRP reports the hourly amounts of EE for their balancing group to the TS operator (hereinafter: TSO) one day ahead. By comparing the real, realized hourly values and the reported position for BRP, TSO calculates the cost of imbalance on an hourly basis for each BRP [14]. Realization that in the observed hour differs from the reported position (e.g. a rainy day instead of a sunny one and the production of solar power plants is significantly below the planned, sudden stoppage of work of a large industrial end customer due to an accident and his consumption is 0 kWh instead of the significant one that was planned, or a sudden unplanned increase in consumption, e.g. heating of a large number of households with devices that work on EE due to failure of the district heating) will cause significant imbalance costs for the BRP in question. Precisely in such situations, when there are no DSO orders for the aggregator, the aggregator can play a key role in reducing the costs of the BRP imbalance. In the event of an unplanned reduction in consumption, he can reduce the production of EE controlled power plants, increase the consumption of other end customers, reduce the delivery of EE from storage, etc. and vice versa in the event of an unforeseen increase in needs in the observed hour for BRP. In the described way, the aggregator, which is also the BRP, will have income from ensuring the flexibility of the DSO, but also a significant reduction in costs of the imbalance of its balance group.

Therefore, the aggregator, through its functioning, can bring financial benefits to the aggregator itself, but also to the supplier, BRP, as well as to the members of the aggregated group. Furthermore, aggregators have a significant positive impact on DSO in terms of increasing the flexibility of DS (general and local) e.g. by shifting consumption from the part of the day in which DS is overloaded to the part of the day in which the load on DS is less, better balancing of the entire DS, neutralization of the effect of intermittent production of variable EE sources, reduction of losses in DS, integration of new production capacities from renewable sources without large investments in DS , as well as increasing the flexibility of TS and delaying investments in it. Also, the action of the aggregator can replace the management of expensive production capacities by managing consumption, storing or using stored EE or activating production units whose management is cheaper.

5. METHODS OF MANAGING PRODUCTION AND CONSUMPTION IN AGGREGATED GROUP

Aggregators can manage production and consumption by issuing orders to increase/decrease production, i.e. consumption to market participants that they aggregate. Market participants can implement the order of the aggregator in full or to a lesser or greater extent than the given one. Another way of management is automatic, where the aggregator remotely issues an order to automation that physically reduces/increases consumption, i.e. production. For this type of management, a certain level of technical equipment of the members of the aggregated group is required, whereby those who already have the possibility of automatic management with relatively small financial investments can realize the requirements of the aggregator. For other members of the aggregated group, it is necessary to make an assessment of the profitability of automatic management compared to management through the classic order of the aggregator. The second model is significantly more reliable than the first, because it does not depend on the member of the aggregated group, but its consumption or production is automatically reduced or increased by the aggregator. In both cases, the aggregator must take care of both the issued order and its execution. In the literature, it is suggested that the independent aggregator shall be equally responsible for its imbalance (the difference between the issued order and its realization) [18].

In the Republic of Serbia, there is the possibility of remote control of boilers on EE, ETS heaters and instantaneous water heaters with some end-customers from households category. A special tariff for access to DS is defined for the specified manageable consumption [9]. DSO's experiences have shown that this concept is used by a small number of end customers, with negligible amounts of EE, and does not have a major impact on the flexibility of DS. However, the described management model can be an initial idea for the further development of remote consumption management, because heating and cooling systems have significant potential for increasing the flexibility of DS, as well as large industrial consumers with separate consumption that can be directly managed.

6. PREREQUISITES FOR FUNCTIONING OF THE AGGREGATOR

The prerequisites for the successful functioning of the aggregator are, first of all, a precise forecast of the production and consumption of EE within the aggregated group, as well as the monitoring of the realized production and consumption in real time. The production forecast is influenced by many parameters depending on the type of production facility (location, temperature, wind speed, irradiation, etc.). Consumption forecasting is also extremely demanding, in terms of different types of end customers, their habits and activities. Furthermore, both consumption and production depend on the time of day and year.

Smart meters, provided in [1], are necessary so that aggregators can monitor the production and consumption of the aggregated group at any time, as well as the response to orders issued by them to change consumption, i.e. EE production [19]. In 2020, in the Republic of Serbia, TSO had metering devices at all metering points with the possibility of two-way measurement (from the grid and to the grid), data storage, tariff management, remote reading by TSO, as well as by users through the application, etc. [20]. At DS, the situation is somewhat different, where a smart meter is installed at 1.6% of end customers' handover points, as well as at 99% of producers [20]. Due to the described situation with EE measurement, DSO created predefined, substitute load profiles [12] which are used for calculation of the hourly consumption of individual end customers based on their monthly consumption. By applying predefined load profiles, the specific consumption of individual end customers are ignored, and it is not possible to obtain a completely realistic picture of their actions. In order to facilitate and improve the operations of DSO and aggregators, more intensive market development, better reaction of market participants to price signals, as well as to increase flexibility and reduce losses in DS, DSO is intensively working on the development of smart meters.

In addition to the above, it is necessary to work on the improvement of DS management, digitalization of DSO, data protection systems and more efficient data exchange with users of DS and TSO [21].

7. EXAMPLE OF THE NEED FOR INCREASING THE FLEXIBILITY OF DS IN THE CURRENT PRACTICE OF DSO

By increasing the number of production capacities connected to DS, DSO faces the problem of injecting EE into TS. The described phenomenon is primarily observed in the case of the connection of huge production capacities in areas with generally low consumption (e.g. devastated areas, mountainous uninhabited or sparsely populated areas). Given that in the described case the basic principle that produced EE must be consumed is not fulfilled at the DS level, EE goes to TS. In 2017, the first amounts of EE were delivered to TS in the amount of 3 GWh, and 12 GWh would be delivered already in 2020 [20]. The tariff for the delivery of EE from DS to TS (at 110 kV voltage level) has not been determined [9], and DSO delivers the subject EE to TS without compensation. TSO considers the described EE as the production of a virtual power plant that it further delivers to its system users (among others, DSO) and calculates TS access for it.

In addition to the mentioned financial loss, the EE in question increases losses in DS, and therefore costs for them, and additionally burdens DS. Given that the described phenomenon most often occurs in areas with a poorly developed network, network reconfiguration is not possible. By defining the new tariff system, which was described earlier, as well as choosing a suitable point for the connection of production facilities, and especially by the operation of aggregators, the described problem can be successfully solved by harmonizing consumption in the given areas with production, and adapting production to the real needs of consumers.

The above example is just one of the many challenges that the DSO is currently facing and will face in the future. Therefore, in the future, the actions of the aggregator, as well as the orders issued by the DSO, may be of a general nature for the entire aggregated group, but also localized to a certain geographical area (i.e. to a part of the aggregated group) in which overloading/under loading occurs.

8. EXAMPLE OF AGGREGATOR WORK IN THE ELECTRICITY MARKET

8.1 Description of the data used in the calculations

Within this paper, a practical example of some of the possible modes of operation of the aggregator will be given, as well as financial benefits for the aggregator and members of the aggregated group, as well as benefits for DSO in terms of greater flexibility.

233 households that are fed from one transformer station (hereinafter: TS) were observed, where each of them has a smart metering device with the ability to detect and save hourly data, as well as remote reading. For the purposes of this paper, their EE consumption was used on an hourly as well as a monthly basis. Monthly amounts of EE were used by DSO to calculate access to DS households that were taken as an example [1, 9] during 2022. Some data on the hourly consumption of EE for some of the metering points were missing, which is expected considering the type of metering devices and the technology of collecting hourly data [22]. The missing hourly data were estimated based on the monthly consumption of the observed household and the consumption profile defined by the DS Rules of Operation [1, 12].

Based on the available measured and estimated hourly data on EE consumption of all observed households, the hourly consumption of the average household supplied from the observed distribution TS (hereinafter: average household) was determined. The active EE consumption of the average household, by month in 2022, and by tariffs – higher and lower [9] is shown in Figure 4.

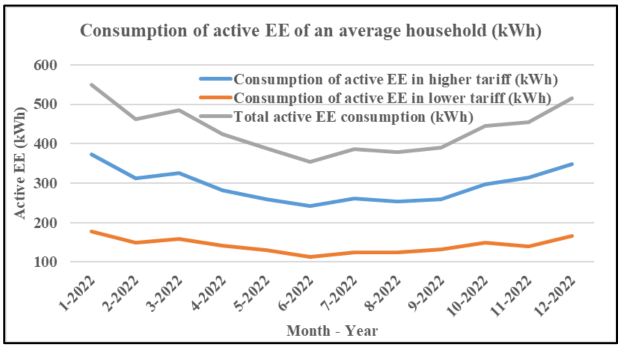


Figure 4. Active EE consumption of the average household in 2022 (kWh)

The average hourly consumption of active EE by month in 2022 of the average household is shown in Figure 5.

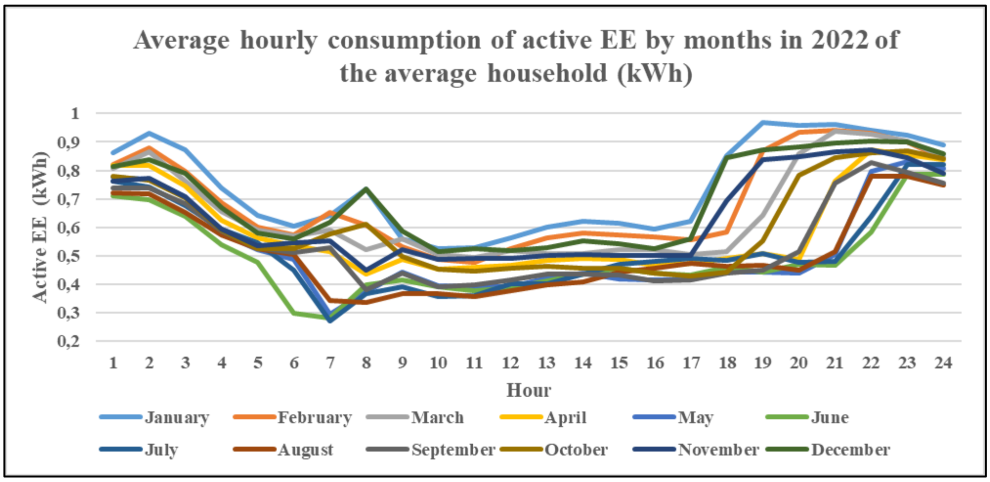


Figure 5. Average hourly consumption of active EE by month in 2022 of the average household (kWh)

8.2 Possibilities for increasing the flexibility of DSO at the level of an average household

From Figures 4 and 5 it can be concluded that in all months the consumption of active EE is low in the period from 8 a.m. to 5 p.m. which is expected because this is household consumption during working hours. After 5 p.m. there is a sudden increase in consumption that lasts until 9 p.m., 10 p.m. followed by a renewed drop in consumption that lasts until the morning hours. This specific example also confirms the justification of the proposal to change the tariff system described in chapter 2.2. However, the displayed consumption diagram provides many possibilities for improving the flexibility of DSO based on consumption management (shifting consumption from the period 5-9 p.m. to the period 0-8 a.m. or to the period 8-5 p.m.).

If the average household would build its own facility for the production of EE from renewable sources and connect it to its internal installations and thereby acquire the status of prosumer [1, 2, 3], the possibilities for consumption management would be even more diverse with a more pronounced favourable influence on the prosumers, BRP, aggregators and suppliers (financial savings and profit), as well as on DSO (less burden on DS, less losses, easier management). Figure 6 shows the prosumer exchange of EE, which is an average household, with DS by month, while Figure 7 shows the exchange at the level of an average hour on an annual level. In the calculations, a production facility with optimal installed power was used to meet the needs of the prosumer, which is an average household.[2] [23, 24].

To determine the optimal installed power of a photovoltaic power plant, it is necessary to know the solar energy resources at the target microlocation, the geographical latitude, the characteristics of the system elements and the ambient conditions [24, 25]. The optimal installed power was determined using the PVGIS[3] software package and its integrated databases [26]. Based on calculations from the program package PVGIS, data on the hourly production of the optimal solar power plant for the average household was also taken.

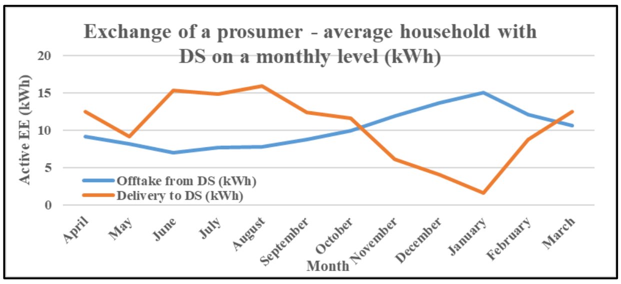


Figure 6. Exchange of a prosumer - average household with DS on a monthly level (kWh)

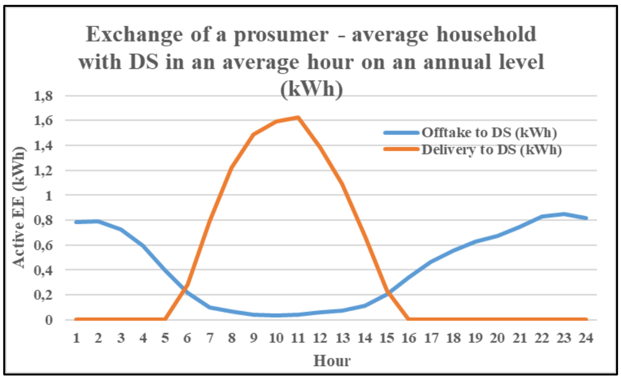


Figure 7. Exchange of a prosumer - average household with DS on an annual level (kWh)

In Figure 6, it can be observed that the delivery to DS is significantly higher than the offtake from DS in the summer months, while in the winter the situation is

[2] For the purposes of this paper, it was assumed that the production facility of the prosumer is a solar power plant, because all prosumer connected to DEES until the date of writing this paper installed solar power plant [23]. It is expected considering the amount of investment and the later relatively low needs for maintenance.

[3] PVGIS is a free online software package. It can be used for estimation of the production of solar power plants, for any location in Europe. For calculations, it uses databases on solar radiation, ambient temperature, wind speed and terrain characteristics based on satellite images. [26]

reversed. From Figure 7, as expected, delivery to DS is significantly higher in the period from 6 a.m. to 3 p.m.. from offtake of EE, while in other periods of the day the situation is reversed. This leads to the conclusion that consumption management is fully justified with the aim of moving it from the part of the day when the solar power plant does not produce EE to the part of the day when it produces EE. This is exactly how the minimum exchange of EE with DS is achieved, which brings all the previously described benefits for the prosumer itself, its supplier, BRP as well as DSO.

In addition to all of the above, the installation of storage, or the use of e-vehicle batteries as EE storage [5] can replace consumption management by storing EE in periods when the production facility produces EE and then using it in periods when the production facility does not produce EE. The best results would, of course, be obtained from a combination of consumption management and EE storage.

8.3 Possibilities for increasing the flexibility of DSO by aggregating EE production and consumption

If all observed households (233 of them) that are fed from the observed TS were members of one aggregated group, the potential for increased flexibility would be even more significant. Figure 8 shows the diagram of the consumption of all 233 households together, if only 20% of consumption in the period from 6 p.m. to 9 p.m. was moved to the period from 8 a.m. to 4 pm.

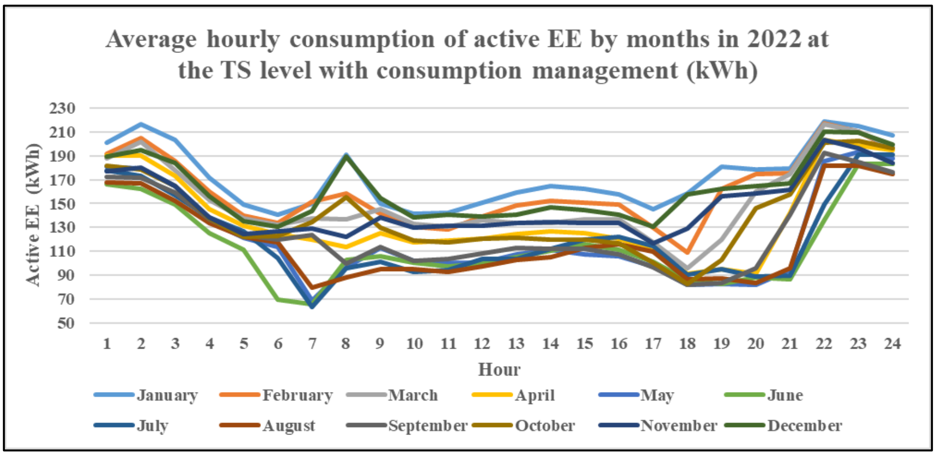


Figure 8. Average hourly consumption of active EE by month in 2022 at TS level with consumption management (kWh)

Analyzing the diagram from Figure 8, and comparing its shape with the diagram in Figure 5, it can be concluded that the described minimum consumption management can contribute to the savings of end customers in case of changing the tariff system and dynamic prices of EE, as well as easier planning of BRP work. This can lead to a reduction in balancing costs, i.e. an increase in income for BRP and aggregators. Also, DSO can more easily manage DS (a more balanced consumption diagram), and there will be less load on DS in terms of reducing peaks, i.e. increasing minimum consumption.

If some of the households that are members of the observed aggregated group acquire the status of prosumer or install electricity storages (or both at the same time), the positive effects of the work of the aggregator in question would be more visible, and its business easier to maintain and more profitable.

The above would be even more noticeable if the aggregated group included solar power plants as well (one or more of them) whose production meets the needs of end customers of members of the aggregated group. Figure 9 shows a diagram of the average hourly consumption or production of EE on an annual basis in the case of the observed 233 households and a solar power plant with optimal installed power. In production calculations, the program package PVGIS was used [26]. Figure 9 shows the production or consumption within the observed aggregated group at the level of an average hour on an annual basis.

If the aggregated group included solar and wind power plants and biomass power plants, due to the nature of their production, the positive impact on the flexibility of DSO, BRP, suppliers and aggregators would be even better. An additional potential of the aggregator can be the storage of EE as part of the aggregated group. EE can be stored in periods of lower EE price and delivered from storage in periods of higher EE price and can also work to reduce BRP balancing costs, as well as to increase DSO flexibility through aggregation.

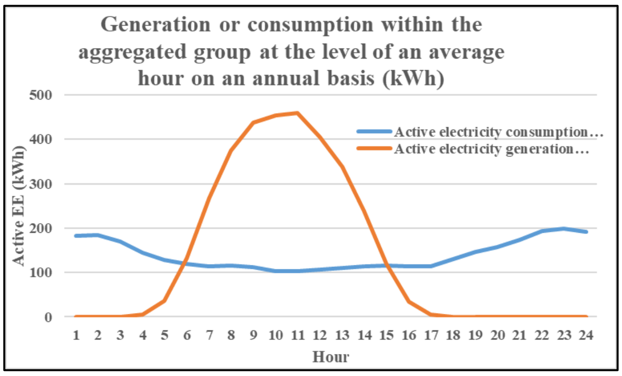


Figure 9. Generation and consumption of EE within the aggregated group at the level of the average hour on an annual basis (kWh)

8.4 The impact of the aggregator's work on the members of the aggregated group, other market participants and DSO

The aggregator can manage the members of the aggregated group in the manner described in chapter 4. In this way, which is shown in the concrete example within this chapter, the aggregator can generate income on the market of ancillary services [6], reduce the costs of BRP imbalance as well, because by operation of the aggregators, the production or consumption of the aggregated group can be planned more easily or the implementation adapted to the plan. Members of the aggregated group can have financial savings, i.e. additional income, from compensation by the aggregator in case of its action, as well as from adjusting the offtake of EE from DS in periods of lower prices, i.e. delivery of EE to DS in periods of higher EE prices in the case of a contract with the supplier with dynamic prices [6], i.e. EE consumption from its own production facility in case of prosumers. Through the desired effect of the aggregator, DSO can increase flexibility, i.e. provide more EE in DS when there is not enough of it or provide greater demand for EE when there is more in DS than needed (example given in chapter 7). The aforementioned facilitates the management of DS, reduces or postpones the need for additional investments in DS and TS, and leads to a reduction of losses in DS and TS [27].

All the described effects would be even more pronounced in the case of aggregation of the consumption of end customers with higher EE consumption (e.g. industry) because there are greater opportunities for consumption management and exploitation of EE storage capacity, and the impact on the flexibility of ODS would be more significant, as well as financial effects on the end customers, suppliers, BRP and aggregators because the price of EE for end customers who are not households and small customers is not regulated [1, 28] it is market price (Figure 3), that is significantly higher. The effects would of course be significant even if the members of the aggregated group were only households (as in the given example), EE producers from renewable sources and storage, especially bearing in mind that a large number of them are connected to DS. For the sake of illustration, at the end of 2021, a total of 3,307,538 metering points for households were connected to DS, and slightly more than half of the total EE delivered to DS users [8] was delivered to them.

An aggregator that aggregates production and consumption that is geographically grouped, for example, could contribute to an additional increase in the flexibility of the DSO at the TS level. However, although desirable, it is not a prerequisite for the functioning of the aggregator, and DS users do not have any restrictions when choosing an aggregator.

In addition to all of the above, aggregators, through their work, which is described in this paper, contribute to the reduction of environmental pollution and the transition to renewable energy sources.

9. REGIONAL EXAMPLE OF REGULATION FRAMEWORK FOR AGGREGATORS

Until the date of writing this paper, the member states of the European Union have, to a greater or lesser extent, transposed the provisions of the Directive on common rules for the internal market for electricity [6] into their legislation, which basically regulates the position of aggregators on the EE market. The Republic of Serbia as a EU candidate country is in the process of harmonizing its legislation with the "acquis communautaire", and will therefore be obliged to transpose the provisions of this directive in its legislation in the future. The Republic of Croatia, as a member state of the European Union, has transposed this directive in its legislation. It represents a country with a similar legal tradition as the Republic of Serbia, and the electric power system (hereinafter: EES) in these two countries has been developing in a similar way for decades. Therefore, in order to meet the more detailed regulation of aggregators in the Republic of Serbia, this paper will present the regulations related to aggregators in the Republic of Croatia.

In general, the issue of aggregators in the Republic of Croatia is dealt with by the EE Market Law (hereinafter: the Market Law) [29] as well as other regulations such as the General Conditions for the Use of the Network and the Supply of EE [30], Rules on Changing Suppliers and Aggregators [31] adopted by the Croatian Energy Regulatory Agency (hereinafter: CERA), which regulate the conditions and procedure for changing suppliers and/or aggregators with regard to the supply of EE, the purchase of EE and aggregation.

In terms of the Market Law, an aggregator is defined as a market participant engaged in aggregation, an independent aggregator is an aggregator that is not connected to the supplier of end customers, i.e. it is not a related entity to the supplier of end customers, while aggregating is considered an activity performed by a natural person or legal entity which can combine the power and/or the electricity taken from the network of several customers, or energy storage operators, or the power and/or the electricity delivered to the network of several producers or active customers or operators of energy storage, for the purpose of participating in any electricity market. Furthermore, the law stipulates that aggregation is an energy activity [29].

This law prescribes the rules for change and the rules on fees for changing suppliers and aggregators, which stipulate that this change should be carried out in the shortest possible time without compensation, except in the case when the system user voluntarily terminates the contract with the aggregator, that stipulates a mandatory duration and fixed prices. A special article regulates the rules related to the aggregation contract, which also stipulates the rule that suppliers may not subject end customers with whom they have a supply contract to discriminatory conditions, requirements, procedures and mandatory additional fees, based on the fact that they have a contract for aggregation [29].

Article 28 of the Market Law sets out the rules for managing consumption through aggregation, which provides that the end customer can independently or through aggregation participate equally in all EE markets in accordance with the rules governing individual EE markets, and that the aggregator can be a participant in all markets EE in accordance with the rules governing individual EE markets. It is clearly stipulated that the supplier may not charge its end customer who has concluded a contract with an independent aggregator unjustified costs or liquidated damages, i.e. impose other unjustified contractual restrictions of discriminatory, technical, management requirements or procedures, as well as that the end customer who independently or through an independent aggregator participates in consumption management pays a fee to its supplier who is directly affected by the activation of consumption management. The character of the said compensation is also determined, so among other things it is stipulated that the compensation is strictly limited to covering the costs of the customer's supplier who participates in consumption management through aggregation, the costs of the customer's supplier who independently participates in consumption management, or the costs of the supplier's BRP, which are caused by the activation of consumption management.

The aforementioned system of rules in the Republic of Croatia creates a clear and transparent basis for the development of aggregators and increase of their number and functionality, which will contribute to the strengthening of auxiliary systems for the supply system as well as DS in the Republic of Croatia. On the other hand, despite the fact that in the Republic of Serbia a set of by-laws related to aggregators has not yet been adopted, experts have begun to consider their importance and role for the EES, and the presentation of regulations on aggregation in the Republic of Croatia should contribute qualitatively to this. Completing the necessary regulation should provide the solution of the challenges aggregators are facing and ultimately, among other things, enable DS to work more efficiently.

10. CONCLUSION

In the previous period, a significant number of new participants in the EE market were included in the legislation of the Republic of Serbia. Some of them already existed in practice and performed their function, for example, e-vehicle charging stations, while some others such as the aggregator are yet to come to life. The prerequisite for this is defining regulatory rules so that all participants in the process can have certainty about the procedures and standards that are needed so that aggregators operating on the market of the Republic of Serbia could fulfil its role.

The development of aggregators, besides the producers, consumers and aggregators themselves, should bring the most benefit to EES itself, so that the aggregators would help in periods of high production or high consumption, by managing the members of their aggregated group and providing support for the stable and efficient management of the EES. Therefore, the biggest support for the introduction of this participant in the EE market should be DSO and TSO, as potential future daily users of aggregator services.

The adoption of legislation related to aggregators is only the beginning towards the promotion of the aforementioned benefits for EES. Further development of regulations in this area should contribute to more energy-efficient use of EE by prescribing clear rules that will enable minimizing of inefficient forms of consumption as well as production. The solutions presented in this paper, including the regional practice, serve to familiarize the legislators with certain aspects of the topic related to aggregators and to use them when considering the content of future relevant acts. The paper is also intended to reach wider professional public that has an interest in understanding the nature and importance of the aggregator before its implementation in practice.

BIBLIOGRAPHY

[1] Zakon o energetici ("Sl. glasnik RS", br. 145/2014, 95/2018 - dr. zakon i 40/2021)

[2] Zakon o korišćenju obnovljivih izvora energije ("Službeni glasnik RS", br. 40/21)

[3] Uredba o kriterijumima, uslovima i načinu obračuna potraživanja i obaveza između kupca – proizvođača i snabdevača ("Službeni glasnik RS", br. 83/2021 od 27.8.2021. godine, 74/2022 od 01.07.2022.)

[4] Dostupno na: https://www.mre.gov.rs/lat/aktuelnosti/javni-pozivi/javni-poziv--za-dodelu-sredstava-za-finansiranje-programa-energetske-sanacije-porodicnih-kuca--solarni-paneli--koji-sprovode-jedinice-lokalne-samouprave-kao-i-gradske-opstine--jp-3-21, [pristupljeno 07.04.2023. godine]

[5] Kuzman M., Grujić D., "Punionice električnih vozila na tržištu Republike Srbije", CIRED 2022, Kopaonik

[6] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU ("Official Journal of the European Union", No. L 158/125).

[7] HUPX Historical data, dostupno na: https://hupx.hu/en/market-data/dam/historical-data, [pristupljeno 07.04.2023. godine]

[8] Energetski podaci 2021, Elektrodistribucija Srbije d.o.o. Beograd, dostupno na: https://elektrodistribucija.rs/o-nama/informacije/dokumenta/GI_ODS_2021.pdf , [pristupljeno 07.04.2023. godine]

[9] Odluka o utvrđivanju Metodologije za određivanje cena pristupa sistemu za distribuciju električne energije („Službeni glasnik RS", broj 105/12)

[10] SEEPEX tržišni podaci, dostupno na: http://seepex-spot.rs/sr/market-data/day-ahead-auction, [pristupljeno 07.04.2023. godine]

[11] International Renewable Energy Agency, Aggregators Innovation Landscape Brief, str. 12, dostupno na: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF, [pristupljeno 07.04.2023. godine]

[12] Pravila o radu distributivnog sistema, jul 2017. Godine, dostupno na: http://aers.rs/FILES/AktiAERS/AERSDajeSaglasnost/2017-07-19_Pravila%20o%20radu%20ED-ODS%20EPS%20distr.pdf, [pristupljeno 07.04.2023. godine]

[13] Pravila o radu prenosnog sistema, mart 2020. godine, dostupno na: https://ems.rs/wp-content/uploads/2022/07/PRAVILA-O-RADU-

PRENOSNOG-SISTEMA.pdf, [pristupljeno 07.04.2023. godine]

[14] Pravila o radu tržišta električne energije, novembar 2022. godine, dostupno na: https://ems.rs/wp-content/uploads/2022/12/Pravila-o-radu-trzista-elektricn-1.pdf , [pristupljeno 07.04.2023. godine]

[15] Naval N., Yusta J., „Virtual power plant models and electricity markets - A review“, Renewable and Sustainable Energy Reviews Volume 149, October 2021, 111393, dostupno na: https://reader.elsevier.com/reader/sd/pii/S136403212100678X?token=65B314150E74FF7E9307D6D02FEF118364DE7D599CDFE5979E2D60FC70A69285B5280C1FFEA6FF7A99A1E860F91F533F&originRegion=eu-west-1&originCreation=20230407152242, [pristupljeno 07.04.2023. godine]

[16] Ma Z., Billanes J., Jørgensen B. N., "Aggregation Potentials for Buildings—Business Models of Demand Response and Virtual Power Plants"; Energies, October 2017, 10(10):1646; DOI: 10.3390/en10101646

[17] Bahloul M., Breathnach L., Cotter J., Daoud M., Saif A., Khadem S., „Role of Aggregator in Coordinating Residential Virtual Power Plant in "StoreNet": A Pilot Project Case Study"; IEEE Transactions On Sustainable Energy, Vol. 13, No. 4, October 2022, pp. 2148-215; DOI: 10.1109/TSTE.2022.3187217

[18] Vukovljak M., Janković M., „Novi učesnici na tržištu električne energije“, Cigre Srbija, Zlatibor, 2021.

[19] Zajc M., Kolenc M., Suljanović N., "Virtual Power Plant Communication System Architecture"; Control, Communication, and Optimization of Smart Power Distribution Systems, 2019, pp. 231-250; DOI: 10.1016/B978-0-12-812154-2.00011-0

[20] Izveštaj o radu Agencije za energetiku za 2020. godinu, dostupno na: https://www.aers.rs/Files/Izvestaji/Godisnji/Izvestaj%20Agencije%202020.pdf, [pristupljeno 07.04.2023. godine]

[21] Kerscher S., Arboleya P. "The key role of aggregators in the energy transition under the latest European regulatory framework", International Journal of Electrical Power & Energy Systems, Volume 134, January 2022, 107361

[22] Funkcionalni zahtevi i tehničke specifikacije AMI/MDM sistema, sveska 1, Tehničke specifikacije brojila električne energije i komunikacionih uređaja, verzija 4.0, Usvojeno na Stručnom savetu EPS Distribucije, Beograd, 07.02.2019. godine, dostupno na: https://elektrodistribucija.rs/interni_standardi/pravila/Specifikacija_verzija%204.0_Sveska_1_Usvojeno_na_TSS_EPSD_07022019_objaviti.pdf, [pristupljeno 07.04.2023. godine]

[23] Registar kupaca-proizvođača, Elektrodistribucija Srbije d.o.o. Beograd, dostupno na: http://edbnabavke.edb.rs/registar_kupaca/DOMACINSTVA/DOMACINSTVA.pdf, , http://edbnabavke.edb.rs/registar_kupaca/STAMBENA_ZAJEDNICA/STAMBENA_ZAJEDNICA.pdf, http://edbnabavke.edb.rs/registar_kupaca/OSTALI_KP/OSTALI_KP.pdf, [pristupljeno 07.04.2023. godine]

[24] Grujić D., Kuzman M., "Modeli korišćenja električne energije kupaca-proizvođača", Energija, ekonomija, ekologija, 2022, god. XXIV, br. 1, str. 8-16.

[25] Grujić D, Đurišić Ž, „Uslovi razvoja projekta solarne elektrane u sklopu TS „Beograd 20“, CIGRE Srbija, Zlatibor 2015.

[26] Climate online baze podataka, dostupno na: https://re.jrc.ec.europa.eu/pvg_tools/en/ [pristupljeno 07.04.2023. godine]

[27] Rajaković N., Tasić D., „Distributivne i industrijske mreže“, Akademska misao, Beograd 2008.

[28] Odluka o regulisanoj ceni električne energije za garantovano snabdevanje sa primenom od 01. januara 2023. godine, https://www.aers.rs/FILES/Odluke/OCenama/2023-01-01%20odluka%20EPS%20struja.pdf [pristupljeno 07.04.2023. godine]

[29] Zakon o tržištu električne energije ("Narodne novine", br. 111/21)

[30] Opći uvjeti za korištenje mreže iTSOkrbu električnom energijom ("Narodne novine", br. 104/20).

[31] Pravila o promjeni opskrbljivača i agregatora ("Narodne novine", br. 84/2022)

BIOGRAPHIES

Dunja Grujić completed her undergraduate and master studies at The University of Belgrade School of Electrical Engineering, where she is currently a PhD student at the Power Grids and Systems module. She is currently employed at Elektrodistribucija Srbije as a senior analyst for business processes for market support and loss reduction. She actively participates in the work of the working groups of the Energy Community, as well as in the drafting of legal acts and by-laws in the field of energy. She has published several scientific papers on integration of renewable energy sources, as well as the electricity market.

Miloš Kuzman is an energy law consultant with considerable experience in the field of legal support to oil and gas exploration and production. He specializes in the field of energy, commercial, banking and financial law, and gained experience, among other things, at master studies at the Institute for Law and Finance in Frankfurt am Main and Columbia Law School in New York. He is currently in the position of Senior Upstream Advisor in the Petroleum Industry of Serbia, is a PhD student in the field of energy law and is the vice president of the Serbian Energy Law Association.

UDK: 621.131.1:502.131.1(497.11)
620.9:339.13(497.11)

Dunja S. Grujić[1], Miloš M. Kuzman[2]

Uloga agregatora u razvoju tržišta električne energije

[1] Elektrodistribucija Srbije d.o.o. Beograd, Beograd, Republika Srbija*
[2] Udruženje za pravo energetike Srbije, Beograd, Republika Srbija

Kategorija rada: pregledni članak

Ključne poruke

- Agregatori kao novi učesnik na tržištu
- Značajan činilac zelene tranzicije – agregator
- Efikasna optimizacija proizvodnje i potrošnje električne energije
- Uticaj na fleksibilnost elektroenergetskog sistema

Kratak sadržaj

Poslednjih godina došlo je do ubrzane tranzicije distributivnog elektroenergetskog sistema iz pretežno pasivnog u aktivan pre svega usled porasta broja proizvođača električne energije iz obnovljivih izvora priključenih na distributivni sistem. Pored toga, izmenama i dopunama Zakona o energetici definisani su novi korisnici distributivnog sistema, među kojima i kupci-proizvođači i skladištari čije se masovnije priključivanje na distributivni sistem očekuje u narednom periodu. Kao bitan novi učesnik na tržištu prepoznat je i agregator koji pruža uslugu objedinjavanja proizvodnje i potrošnje električne energije u cilju dalje prodaje, kupovine ili aukcija na tržištu električne energije.

U ovom radu biće analizirani mogući modeli poslovanja agregatora, postojeća zakonska regulativa i preduslovi koji su potrebni za njihovo funkcionisanje na tržištu Republike Srbije. Takođe, u radu će biti predstavljene i dobre međunarodne prakse u ovoj oblasti. Pored toga razmatraće se efikasni načini objedinjavanja proizvodnje i potrošnje električne energije, između ostalog krajnjih kupaca i proizvođača, od strane agregatora.

Biće razmatran i uticaj agregatora na poslovanje operatora distributivnog sistema pred kojim stoje brojni izazovi. Neki od ovih izazova vezani su i za upravljanje sistemom i promene tokova snaga usled priključenja značajnog broja novih korisnika sistema. Na kraju rada će biti prikazan konkretan primer koji ilustruje mogućnost delovanja agregatora u cilju povećanja fleksibilnosti elektroenergetskog sistema.

Ključne reči

Agregatori, upravljanje proizvodnjom i potrošnjom električne energije, energetska efikasnost, obnovljivi izvori električne energije

Napomena:
Članak predstavlja proširenu, unapređenu i dodatno recenziranu verziju rada „*Modeli funkcionisanja agregatora na tržištu električne energije*“, nagrađenog u STK-6 *Tržište električne energije i deregulacija* na 13. Savetovanju CIRED Srbija, Kopaonik, 12-16. septembra 2022.

Primljeno: 7. april 2023. Recenzirano: 22. maj 2023.
Izmenjeno: 26. maj 2023. Odobreno: 27. maj 2023.
*Korespondirajući autor: Dunja S. Grujić
Tel. +381-64-897-46-59 E - mail: dunja.grujic@ods.rs

UDC: 620.9:502.131.1(497.11)
620.9:005.21(497.11)

Vladimir M. Shiljkut (Šiljkut)[1], Nikola Georgijević[2], Saša Milić[3], Aleksandar Latinović[1], Dušan Vlaisavljević[2], Radoš Čabarkapa[1]

Aggregation of Composite Virtual Power Plant - Application Possibilities and Limitations in Serbia

[1] Joint Stock Company „Elektroprivreda Srbije“, Belgrade, Serbia*
[2] Electrical Power Coordination Center, Belgrade, Serbia
[3] „Nikola Tesla“ Electrotechnical Institute, Belgrade, Serbia

Category of article: Review article

Highlights

- A detailed review of the literature on virtual power plants, an overview of concepts and particular solutions is given
- Considered energy sources, methods of aggregation and technical potential for establishing a virtual power plant
- Proposed composite virtual power plant concept, estimated costs, benefits, legal restrictions

Abstract

Serbian power industry increasingly faces the challenges of the future. Electricity generation is based mostly on low-caloric lignite. Its deteriorating quality causes a decline in the level of safety, reliability, and efficiency of thermal power plants, increasing pollution. Beside their revitalization, there are huge investments in new, expensive systems for reduction of pollutants' emissions. With the announced introduction of carbon taxes, which will grow rapidly in the future, the profitability of these power sources and the market competitiveness of the price of electricity obtained from them become extremely questionable and uncertain. In inevitable decarbonization process, a strategic question arises for Serbian experts – how to compensate significant basic (thermal) capacities, which will be probably shut down?

At the other end of the system, the problem is inefficient use of electricity, unacceptably high level of its losses, including those due to its theft. At the same time, the technical possibilities for load management and for the application of a larger number of tariffs were not used sufficiently, to provide the desired demand response.

In such circumstances, the key question is - what investment strategy to choose? This paper proposes a solution that would have a positive impact on both ends of the system and its actors, but also on the networks between them and their operators. "Electric Power Industry of Serbia" could use the announced introduction of aggregator, as a new participant in the electricity market, for a kind of joint venture with its end-users, to establish a composite virtual power plant. It would represent a new, replacement capacity for the power industry, and a source of savings and even income for customers. Such a power plant would include various, dispersed renewable sources, both of electricity and heat, energy storage systems, chargers for electric vehicles, controllable customer load and various demand response programs. By increasing the volume of such aggregation, a composite virtual power plant would enable the aggregator to provide ancillary services to the transmission system operator, which would be an additional benefit. In synergy with other necessary, strategic steps, such a concept could provide Serbia more secure energy future.

Keywords

Aggregation, Ancillary Services, Decarbonization, Demand Response, Distributed Generation, Load Management, Virtual Power Plant

Received: April 7th, 2023 Reviewed: May 9th, 2023
Modified: May 16th, 2023 Approved: May 25th, 2023
*Corresponding Author: Vladimir M. Šiljkut
Phone: +381-64-897-46-72 E - mail: vladimir.siljkut@eps.rs

Note:
This article represents an expanded, improved and additionally peer-reviewed version of the paper "*Aggregation of Composite Virtual Power Plant - A Possible Answer to the Challenges for the Serbian Power System in the Decarbonization Process*", awarded by Expert Committee EC-5 *Distribution System planning* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

1. INTRODUCTION

1.1 Energy issue context in Serbia

Beside functional and organizational unbundling during the previous period of the deregulation process, to the effects of which it is still adapting, the entire electric power sector of Serbia is increasingly facing new, threatening challenges of the future. The primary problem is relying on mostly lignite-based electricity generation over decades. The lignite quality (calorific value) recorded significant deterioration, and its available quantities are questionable. Multiple consequences are reflected firstly in power plants' safety, reliability, and efficiency level decrease, then in additional wear of equipment, and finally in increased air pollution. Thermal power plants (TPPs) are extremely old and therefore demand huge investments not only in rehabilitation but also in the construction of new and expensive (according to investments and exploitation) support systems in the function of environmental protection. Summing up these costs with announced carbon fees which will experience rapid growth in the future, the cost-effectiveness of these sources and the market competitiveness of the electricity price from these sources become very uncertain. Under conditions of inevitable decarbonization in Serbia, there is also an emerging question – which replacement capacities would be used instead of basic (thermal) capacities which are threatened by decommissioning for one or another reason?

Renewable Energy Sources (RES) in the transmission system will compensate a part of the electricity after decommissioning of thermal capacities. Significant integration of variable RES (V-RES) will cause new problems. V-RES have a lower capacity exploitation rate than coal-fired TPPs. For compensation of electricity generated by a coal-fired TPP over a year, it is necessary to build RES of significantly higher installed power, which may cause congestion in the existing transmission network or may limit connecting of new RES. V-RES integration will also condition increased necessary balancing reserve for system balancing in real time, and the system balance creation will also become a problem due to deviation between generation and consumption on a longer, seasonal level.

On the other end of the system, there are also no less of problem represents electricity inefficient use, inacceptable high level of losses, including also the losses due to its unauthorized use. At the same time, technical possibilities for load management or use of potentially larger number of tariff rates for the purpose of desired demand response that are already available are not exploited at all. Interests of supplier and operators of distribution and transmission systems are not necessarily the same, [1]; the supplier tends to sell as much electricity as possible, with as much profit as possible, while the latter strives to maintain a stable system, i.e. not to have the system elements overloaded.

Under such circumstances, long-term planners and creators of development of the power system (PS), as a whole, face a question – which direction to follow, which investment strategy to choose?

This paper suggests a solution to think about that would have a favourable impact on the technical aspect of the system (on both of its ends), and also on its actors, but also on the networks between them and on their operators. Instead of huge investments in the thermal sector of questionable perspective and profitability, the Joint Stock Company "Elektroprivreda Srbije" (Electric Power Industry of Serbia, EPS) could make use of the announced introduction of aggregator as a new participant in the electricity market, [2], for a kind of joint venture with its end-users – electricity customers, to establish multi-energy, composite (i.e. collaborative, cooperative) virtual power plant, [3]-[5]. For EPS, it would actually represent a new replacement capacity, while being a source of savings and potential revenues for customers. Such power plant would include different, dispersed, manageable and non-manageable, renewable sources of, not only electric, but also thermal energy (for example solar collectors for water heating), energy storage systems, chargers for electric vehicles, manageable customers load (ETS heaters, electric water heaters, and boilers) and different programs for demand response. By extension of the volume of such aggregation – through a kind of "capacity improvement" and its flexibility improvement – a composite virtual power plant would enable EPS as an Aggregator to additionally provide ancillary system services to the transmission system operator, such as participation in frequency regulation, as well as providing services to the distribution system operator, which would – within appropriate regulatory framework – represent another source of income for EPS. Synergy of such concept with other actions that are required, as harder reliance on hydro capacities, could provide a safer future to Serbia in terms of energy.

1.2 Virtual power plants – review of bibliography and experiences

1.2.1 Definitions and functions of virtual power plant. The basic motive to create and develop the virtual power plant concept in the world is an increasing share of V-RES. Namely, due to the uncertain and discontinuous (i.e. variable) nature of renewable energy sources such as sun and wind, they may cause problems in the operation of the power system implying system balancing and balance creation problems, power quality problems, efficiency, stability, and reliability problems. The virtual power plant (VPP) concept is designed to facilitate V-RES integration, without menacing system operation stability and reliability, with many other technical and economic benefits. What is actually virtual power plant? In [6] it is defined as a "concept consolidating a diversity of distributed electricity sources, manageable load, and electricity storages for the purpose of participation in dispatching and managing electricity market and network operation in the form of another special power plant." The second definition says that "VPP is a structure of ICT (information and communication technologies – *author's comment*) integrating different types of distributed energy sources, flexible consumers and energy storages, mutually and with other market segments, in real time, through the intelligent (smart) network", [3]. Name of "new teleinformatic system enabling energy resources management" is used in [7]. Thus, VPPs perform the task of flexible management of V-RES consolidation, electricity effective storing, and distribution, in variable scales when necessary.

Researches and modeling of endless possibilities of supplying smart cities using VPP technology are numerous, as well as possibilities of preserving environmental eco-system and energy savings. "Smart cities" represent a model of future city planning and urban development, integrating ICT solutions, as well as mechanisms of energy conservation and struggle against climate change with basic technology known as the Internet of Things (IoT). Since it is based on ICT and (most often) IoT, VPP is the most efficient means of energy distribution for smart cities, [8].

1.2.2 Users, carriers, and methods of aggregation. Another question is who may develop and apply the VPP concept and under which circumstances? VPP concept may be developed by many types of entities / energy entities, for example, distribution system operators, electricity producers, and energy clusters, [7]. There are many solutions due to the very wide range of possible applications, and the possibility of building a system based on modules enables the system to adapt to the needs of users, to change easier, and to integrate into larger systems. Regulations are passed and concepts are applied that enable the development of renewable energy sources, including prosumers and so-called active consumers, and also enable active participation of energy consumers in the energy market. Additionally, more severe requirements for energy production and consumption balancing are introduced which demand higher accuracy of balancing, [7]. Further, we will provide an overview of various solutions that can be found in the relevant bibliography references bellow.

Ref. [9] shows the structures, types, architecture, and operation of VPPs, as well as the situation regarding their application worldwide. VPP types are detailed, with optimization algorithms used for each of them. VPP is connected with most of the components of the power system, such as Distributed Generation (DG), prosumers, Transmission System Operator (TSO) and Distribution System Operator (DSO), and network services including fault elimination, reactive power management, while using communication, management and optimization technologies. The article provides a comprehensive insight into microgrid transformation towards VPP, which may be useful to researchers, consumers, prosumers, and system operators. The essence of the approach used in [9] is that the microgrid with optimization, communication ability, and with an application of artificial intelligence methods, becomes VPP. Automation of microgrids is implied as a precondition of generation and consumption manageability and optimization of the costs of its operation.

Paper [10] provides VPP concepts from the studies of various researchers as well as detailed explanations. Some typical VPP projects around the world are presented. Additionally, some potential challenges and advice for the future development in VPP studies are shown. Three types of VPP users are identified: Standalone, Energy buying, and Energy selling. Independent Power System Operator (IPSO) is a key player, "midfielder", between the external market, with whom it exchanges load forecast data and market information, and the decision-making center, to whom it reports price strategy and from whom it receives results of activities.

1.2.3 Architecture, concepts, and models of VPP. In [11], the concept and the experimental results of a microgrid named District Power Plant, designed to operate as an active element in the local distribution network, capable of providing services such as demand response (DR), active supply, and advanced metering, are presented. Stable operation of both island and reconnection modes of operation of such system is presented, as well as good power quality in both modes of operation.

Paper [12] suggests a new system of the city VPP integrating distributed generation units, systems for energy storing, and controllable load. It applies advanced technologies for communication and coordinated management in order to implement the overall regulation and management of different types of distributed energy and load. Thus the challenges created due to the great share of random and variable distributed generation in power network operation and dispatching are mitigated and the imbalance between supply and demand is reduced. The paper illustrates the suggested architecture of the city VPP system and shows its resources on the side of users.

Efficient management and dispatching are also the subject of the paper [6]. For the purpose of efficient dispatching and management of large number of demand response resources (such as thermally controllable load capacities), this paper studies energy efficiency management system on the basis of a concept grounded on demand response technology and VPP theory and efficiently uses temperature management system. By collecting and controlling the parameters of capacity of resources for load management, making complete use of potential for load reduction on the consumption side, appropriate shifting of peak electrical load is achieved, suitable for mitigation of deviations between supply (electricity generation) and demand and for ensuring safe and stable operation of power grid.

VPP and components of "smart" energy, grid, system, and city are shown and compiled in the article [13]. It presents VPP and appropriate components of "smart" grid that are its integral parts. "Smart" energy structure consisting of subgroups of low-carbon production, efficient distribution and electricity consumption optimization is laid down.

A platform for the integration of different types of Distributed Energy Resources (DER) is presented in research [14]. Various domains of knowledge were necessary to plan and build this platform – telecommunication, electrical engineering, mechanics, automation, informatics, architecture, and sociology. The key thing was defining the scope of the project, harmonizing the specifications, and mutual understanding between the partners (including contractors and subcontractors), as well as defining the common language for efficient cooperation. Besides, it is highlighted that users/hosts have to be as informed as possible during the installation phase and connected to the project during its operational phase. They also want to understand the purpose of intervention and to be aware of when the installed devices are in operation. The criticality of integration of different technologies and standards is emphasized: authorization of http-clients, SSL certificates, web services, Common Information Models (CIM), Smart Energy Profiles (SEM), etc. Under the platform of such an integrated management center subjected to the Aggregator, it is possible to consolidate different users and their devices and dispersed sources; residential (thermal storages and heat pumps, photovoltaic panels, batteries for storage of electricity surpluses, load management), adjustable public lighting, industrial users (production from thermal solar collectors, cold storages), housing and business premises (solar thermal storages, load management), [14].

The notion of Energy Market of Things (EMoT) is introduced, [15]. DER is the historical chance for energy traders which may bring numerous advantages, for example, the possibility to open an abundant offer of flexibility on the side of supply at low and medium voltage, consisting of energy communities, and even small farms of PV panels and batteries. Access to behind-the-meter data which may be used for fine settings of trading and forecasting algorithms is necessary. Devices, starting from heat pumps up to the chargers for electrical vehicles (EV), DER, and power plants and facilities, may now collect and exchange the data (i.e. communicate) and be connected to any type of electricity market.

EMoT enables the networking of physical devices related to electricity, for a small volume of its generation, storing, and electricity flexible consumption, [15]. These “things” have built-in sensors, and dispose of software and other technologies to connect and exchange data with other devices and any type of electricity market – whether it is about local flexibility markets, energy balancing platforms or classic exchanges such as EPEX SPOT, Nord Pool and HUPX. These devices' variation range goes from simple household items to large commercial or industrial devices.

1.2.4 VPP as network or system of cooperation. Ref. [3] presents VPP as a cooperation network. It emphasizes that although VPP is one of the types of virtual organizations, VPP definitions are primarily directed toward its technical aspect while insufficient attention is paid to the management aspect and, particularly, the business model. Therefore, in [3], the legal background for VPP establishment is presented, as well as legal possibilities and threats for VPP creation in Poland. It is emphasized that legal analysis is the starting point for every practical project. Legal regulations related to prosumers and supporting energy micro-clusters are presented. These issues require the creation of new products, e.g., VPP. Then a review of business models is made in order to select an adequate model, [3]. Mainly three types of models are identified; the first model is mainly a characteristic of the relationship between customers, clients, partners, and suppliers; the second model emphasizes the importance of the company's resources which can be expanded and used, and potential sources of future economic benefits; the third model represents a combination of the first two and combines the key resources and key relationships important for VPP (this corresponds to system approach). Based on the selected model, the VPP is structured as a network of cooperation between different types of energy entities. At the same time, the segmentation of possible users of VPP is carried out according to two criteria – according to the type of market and according to the type of product [3].

The trend of convergence of VPP towards collaborative networks is also confirmed in [4,5]. Namely, it is claimed therein that according to its composition, VPP forms a kind of collaborative business ecosystem with a high degree of interaction and interdependence among interested parties. Research [4,5] is focused on analysing the trends and identifying the areas of convergence between the discipline of Collaborative Networks (CN) and the concept of VPP, as well as the development, using prior knowledge from the CN domain. The results show that various strategic and dynamic cooperative alliances are formed within VPP, such as goal-oriented networks, Virtual Organizations Breeding Environment (VBE), opportunity-driven networks, and continuous production-driven networks. Various basic functional principles of VPP are similar to those of CN: creation, operation, and dissolution of virtual organization, negotiations, brokerage services, VBE administrator services, virtual organization planner and coordinator services, and partner search and selection processes, [4,5]. DER share in the energy market is ensured through VPP aggregation, [4]. It includes multiple interested parties: markets/customers, distribution service operators, DER/prosumers/controllers of prosumers, energy management systems, service providers, energy communities and energy cooperation, and regulatory bodies, [4].

Authors of [4,5] developed and discussed in [16], the concept of a collaborative virtual power plant ecosystem (Collaborative/Cooperative/Composite VPP Ecosystem, CVPP-E). It contributes to the efficient organization of Renewable Energy Communities (REC) in such a manner that they can act as a VPP or exhibit its attributes. This concept is derived by merging or integrating the principles of organizational structures and mechanisms from the CN domain into the VPP area. It is expected that, if the actors in REC engage in collaborative actions, it will enable REC to perform functions similar to VPP. Conceptually, CVPP-E consists of a management community, a shared community energy storage system, consumers owning a combination of photovoltaic and battery storage systems, and passive consumers, all connected to the power network. A key attribute of this proposed ecosystem is that its members are engaged in collective actions or collaborative ventures based on a common goal, aimed at achieving sustainable power production, consumption, and sales. Study [16] gives a high-level model for the aspects of cooperation in CVPP-E. This includes the framework of compatible (common) goals, sharing framework, and a framework of collective actions. These frameworks serve as the backbone of CVPP-E and play a vital role in CVPP-E modelling. To evaluate the proposed model, different simulation scenarios were used in [16].

1.2.5 Components of VPP and optimization models. Components that may be covered by the concept of composite VPP, and CVPP are very diverse. Balancing the fleet of wind generators with the portfolio of flexible assets – biogas power plants and capacitor banks – was considered in [17]. The original purpose of the biogas power plants considered in VPP was to make money in the stock market, primarily on the day-ahead market. When these assets become a part of VPP, their task transforms into the maximization of electricity sales profit while ensuring the balancing the fleet of wind generators, which also results in participation in the intraday market. This task is challenging in terms of methods of optimization and price forecasting. In [17], two aspects are considered: optimization and price forecasting. The first one is mixed-integer optimization and sophisticated decomposition methods were developed. As for the latter one, several forecasting methods based on machine learning (ML) are implemented, to maximize the resulting cumulative revenue. Commercial forecasts are also used and the method from [17] recorded competitiveness compared to these forecasts in terms of the resulting cumulative revenue. Special attention is also paid to the robustness of VPP to handle the large amounts of assets it covers. In addition, Robust Model Predictive Control (RPMC) is used to take into consideration many scenarios during decision-making.

CVPP concept possibilities are not limited only to the increase of system flexibility by the combination of different, compatible energy sources. Thus, in [18], in addition to promoting multi-energy complementarity, with the aim of low carbonization, an optimal model for planning the operation of a VPP with carbon capture and waste incineration is proposed, taking into account the coordination of electricity and gas. By introducing a collaborative framework for using a gas plant system for carbon capture – "electricity to gas" (power-to-gas, P2G), the captured CO_2 can be used as a feedstock for P2G, to produce natural gas that is supplied to the gas unit. Additionally, energy consumption for carbon capture and flue gas treatment can be transferred through joint dispatching to mitigate V-RES output power fluctuations, so that electricity obtained from wind and photovoltaic panels can be indirectly dispatchable and used in flexible manner. Considering the high dimensional nonlinearity of the proposed optimization model and the difficulty in solving it, a new Gaussian complex differential evolutionary algorithm was designed in [18] to solve this model. Simulation results show that the proposed model and method can provide peak load shifting capacity and improve the consumption of renewable energy, while effectively reducing the price and VPP carbon emission.

To solve a large number of discrete clusters of different distributed energy resources in rural areas, in [19] an Electricity Retailer (ER) is set as an agent of these clusters through VPP, that is, an ER is integrated with a virtual power plant (VPP-ER). Further, [19] discusses the collaborative mode of "electricity-carbon" transactions and the optimal model of purchase-sale transactions, at two levels. The higher-level model applies the Conditional Value-at-Risk (CVaR) method to establish a coordinated electricity-carbon transaction model for rural VPP-ER. The lower-level model applies the robust optimization theory to measure the risk of wind farm (WF) or solar PV power plant output power uncertainty, to establish the optimal dispatching model for VPP. Thirdly, the model is converted to Karush–Kuhn–Tucker (KKT) optimality conditions to solve the two-stage purchase-sale transaction model. Using the example of an industrial cluster (Henan Lankao), the results show also that the proposed two-stage model can establish a coordinated optimal electricity and carbon trading scheme. The conclusion of the study [19] is that its findings could provide an effective decision-making tool for rural VPP-ER in Chinese electricity market.

Participation of electric power industry in carbon and green certificates trading is an effective, market-based approach to address the negative external effects of electricity generation. In this regard, VPP also proves to be an effective tool. Thus, in [20] VPP is taken as an aggregator for coordination and optimization of carbon and green certificates trading between the electricity purchasers and the final sale of electricity, in order to achieve the goal of maximizing the comprehensive benefit of VPP. First, the mode of operation of VPP that aggregates different types of distributed energy and different users participating in green certificates market and carbon emissions market is analyzed. Second, a two-stage collaborative optimization model of VPP participating in electricity purchase and sale transaction and green certificate transaction is constructed. On the one hand, the costs of electricity purchase and green certificate obtaining are minimized by combining different types of resources for electricity generation in the end purchase of electricity, and on the other hand, the purchased energy is distributed among different types of users when selling electricity, in order to maximize incomes from electricity and green certificates sales, respectively. On that basis, VPP as a whole participates in the electricity market, the carbon emission market and the green certificate market in order to maximize the overall revenue. Finally, VPP was taken as an example to verify the cost-effectiveness and efficiency of the model proposed in [20].

1.3 Content, contribution and structure of the article

Concept of CVPP which - apart from electricity - would also include other types of energy, as proposed by the authors of this article, is presented in Chapter 2. It is based on the vertical concept of the Industrial Internet of Things (IIoT), [21-23], taking into account its advantages both from the aspect of data and information management and processing, and from the aspect of distributed realization and cyber security. Apart from a very wide range of types of distributed resources for energy production and its consumers, the concept proposed in this article considers the position and role of CVPP in a wider environment and also remains open to include individual larger production units or energy storages. When it comes to distributed resources, under the conditions common for Serbia, the most significant and potentially the most effective is the establishment of management functionality over the preparation of sanitary hot water. Additionally, the emphasis was placed on possible contributions to the optimization of operation and flexibility of the system, which would be provided by functional connection and subsuming under the CVPP concept of thermal storages (distributed, both smaller and larger, purpose-built) and potential energy storages (such as water towers) and their management.

Beside technical and technological connecting of various components, on which the CVPP concept is otherwise based, in the event that EPS would appear as an Aggregator, its power generation portfolio management function (so-called "Trade") could, by concluding long-term contracts on electricity supply (Long Term Power Purchase Agreement, LT PPA) with private wind and solar farms' investors, by offering balancing services, contribute to CVPP model proposed herein. Thus, this part of "green" energy would also become one of the components of the proposed EPS concept and portfolio, that energy would be kept in Serbia and made available for optimization of operation and increase of flexibility of the system.

In the manners described above, CVPP would gain additional performance as a tool for optimization of the operation of the system and use of electricity and thermal energy, produced and stored not only within the capacities of EPS and its end users but also of other energy and business entities. All of this, certainly, does not limit independent energy entities from being independent aggregators on the market (offering their services and developing their own VPP concepts), subject to accepted European practice and regulations.

Chapter 3 of this article shows the ways of aggregation of distributed production of prosumers and their consumption. Chapter 4 provides a rough estimate of the effects that could be achieved by introducing and implementing the concept of a composite virtual power plant. In the example shown, only the effects that would be obtained from aggregation of storage tanks for the preparation of sanitary hot water, equipped with remotely controlled thermostats and "smart" switches, were calculated and presented. Chapter 5 provides an overview of the legal framework and current restrictions in Serbia for further development of this concept. At the end of the paper, appropriate conclusions are given.

2. ORGANIZATIONAL STRUCTURE AND TECHNICAL POTENTIAL FOR INTRODUCTION OF COMPOSITE VURTUAL POWER PLANT

The authors of the article recognized three key questions to be answered before investment planning and practical implementation of virtual power plant. The first question refers to production and consumption processes' control and management, the second question refers to technological aspects of different electricity sources and consumption and the third one is of organizational nature, as the spatial dispersion of sources and consumption has to be harmonized, i.e., they have to create a unique network.

2.1 Vertical and hybrid conception of control and management

Application of modern concepts of control, data processing, management, and decision-making implies that many decision-making processes are transferred from the operational level to higher hierarchical levels. The main goal of modern control, management, and decision-making concepts is to reduce operational costs and shorten the time of data analysis and processing. A VPP represents an extremely complex system with a large number of subsystems. Starting from the advantages of vertical concepts of control, management, and processing of data and information, which have become one of the reliable and acceptable solutions of IIoT-based concepts [21-23], Figure 1 shows the proposed structure of EPS future VPP.

Today, new technologies enable fast and cheap two-way communication between customers and energy companies. "Smart" metering devices with the possibility of remote control can monitor, analyse, forward, and/or store data on the consumption of various forms of energy with high selecting frequencies. The availability of hundreds of thousands of time profiles of the load of different consumer groups creates the possibility of applying artificial intelligence (AI) algorithms to group consumers with similar consumption patterns.

Big Data Analytics (BDA) significantly changed business practices in different industries. Large online shopping platforms (Alibaba, Amazon, etc.), that rely heavily on BDA and data on users' previous purchases and behavioural analysis based on browsing history and internet activity, are maybe the most prominent examples [24].

Figure 2 shows a possible BDA scheme applied to PS. The data collection process starts with different sources of information (Figure 2.a)), such as "smart" meters, the electricity market, weather forecasts, wind speed measuring sensors, etc. This data can be subject to the processing (Figure 2.b) and the application of advanced statistical methods and machine learning (ML) techniques (Figure 2.c)), such as time series analysis, clustering, and deep learning in order to generate information about the peculiarities of the entire system that can be applied for the purposes of estimating technical potential and predictive management of resources, [25]. Such information can be used for the benefit of energy companies, their users, and third parties involved in this process (Figure 2.d)).

2.2 Technical potential of end-users

Virtual power plant can integrate (aggregate) end-users in terms of manageable electricity consumption, and when it comes to prosumers, it can also aggregate manageable dispersed electricity generation. The idea advocated in this article is the integration of dispersed production and manageable consumption, and other forms of energy. At the same time, all considered types of energy are viewed in relation to electricity. The end-user can be a household or a business entity (see Figure 1, top left). Virtual power plant can provide and valorise two types of services, balancing and economic dispatch, and accordingly the technical potential of end-users who could increase the capacity of virtual power plants to provide the relevant services to system operators, as the highest rank users, was analysed (see Figure 1, up right).

End-users' electricity consumption is reduced to the conversion of electricity into another form of energy. Electricity is mostly converted into thermal energy, then

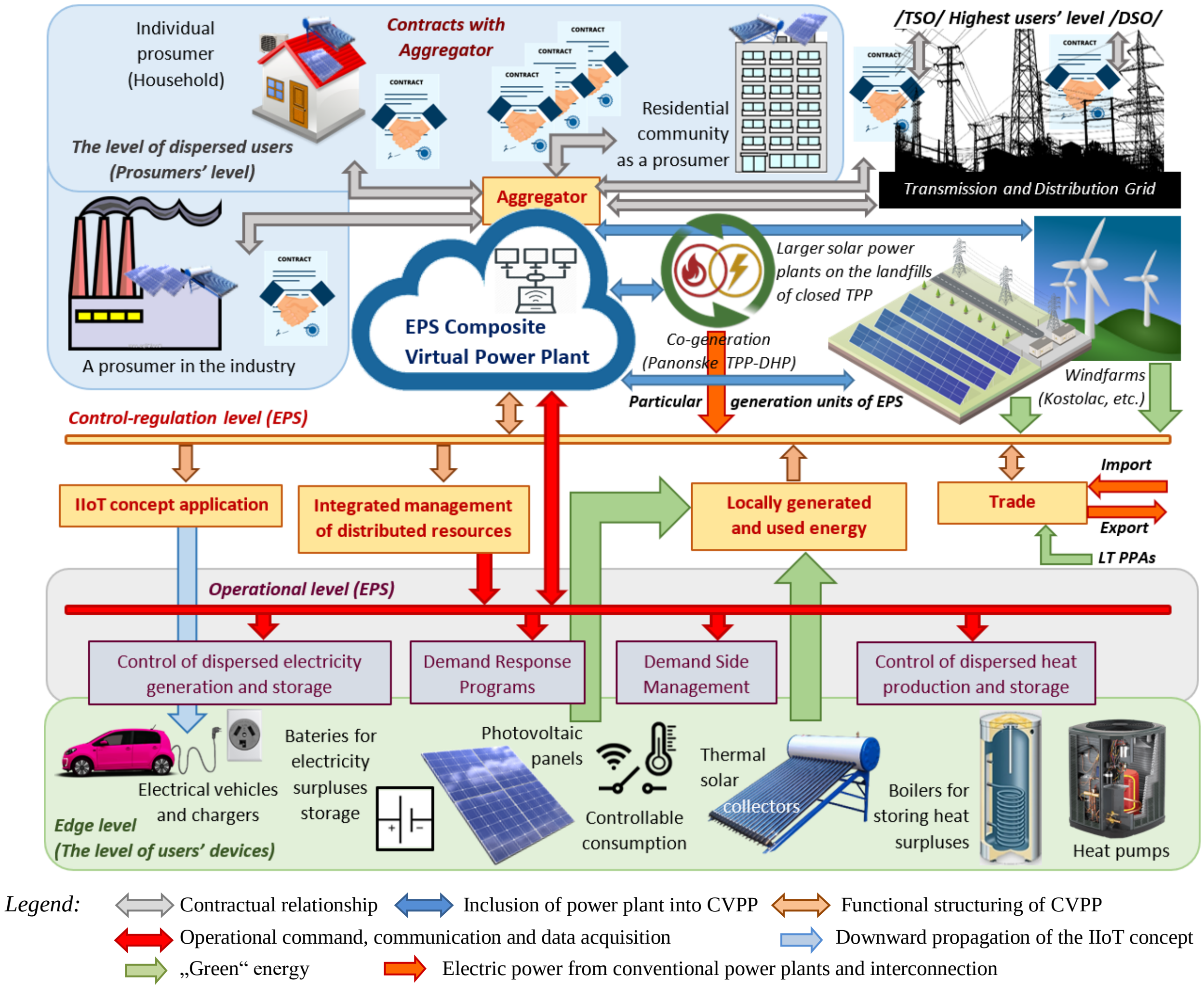


Figure 1 Possible structure, functionality and environment of EPS composite virtual power plant

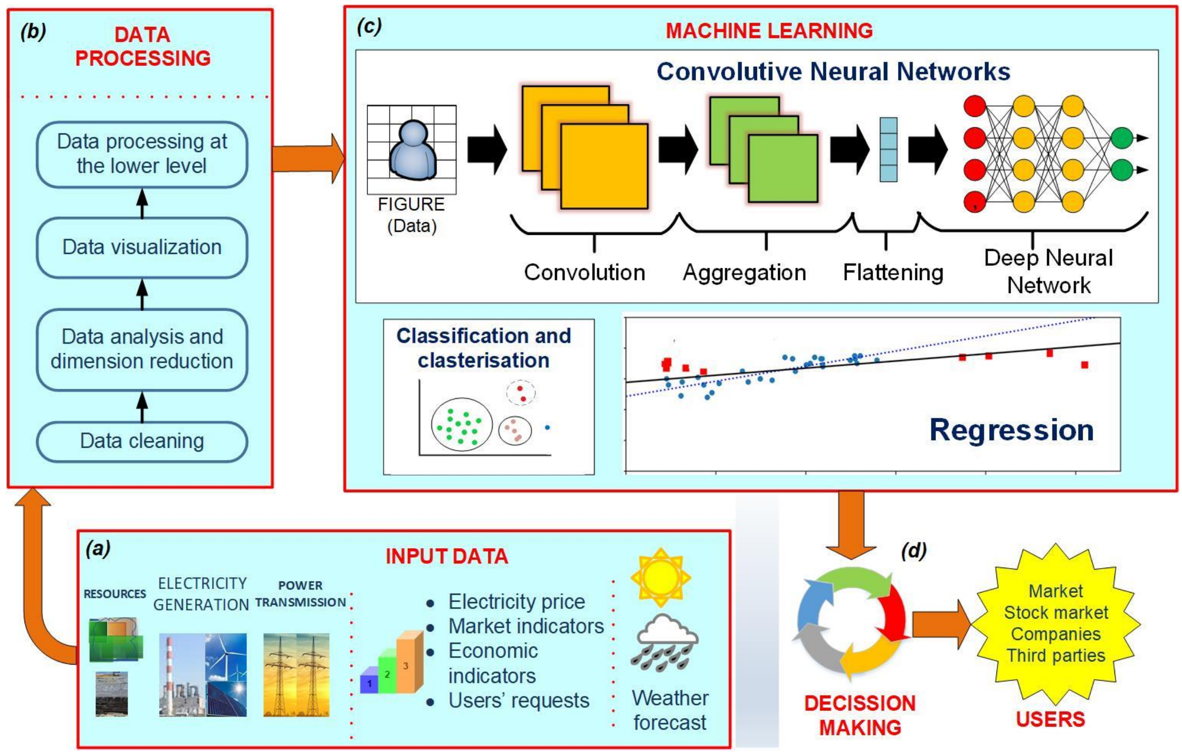


Figure 2 Possible scheme for BDA in EES

into chemical energy, into potential energy or other forms of energy. From the point of view of the virtual power plant, manageable consumption is important, as it has a certain type of energy stored in its technological process, without affecting the technological process of energy consumption. Technological processes consuming electricity, without possessing certain energy accumulations, will not be considered in this article.

Final energy is predominantly spent on heating and cooling processes. In EU28 countries, half of the final energy is converted into heat [26], and for countries that are at a lower level of economic development, that percentage is even higher. In the Republic of Serbia, a rough estimate is that approximately one-third of total electricity consumption in the winter period goes to space heating (average daily electricity consumption in May is around 80 GWh and around 120 GWh in January). With the low cost of heat accumulators, thermal energy consumption represents the most important resource of virtual power plants for both balancing services and economic dispatch. The use of electricity consumption for heat production for the purpose of system balancing is already applied. In Belarus, [27], for the purposes of system balancing, about 1200 MW of manageable electric water heaters were installed for the needs of district heating and preparation of hot water for citizens.

Electricity consumption for the purpose of converting it into chemical energy is most increasing. It's about batteries, and dominant growth is represented by electric car batteries. The direction of battery charger development is not in favour of manageable consumption. Manufacturers of electric cars invest considerable resources to reduce the charging time of batteries by increasing the power of chargers, hence the chargers reach powers of 400 kW, [28]. Electric car batteries during the charging process, in conjunction with "smart" chargers, can become a significant resource for consumption management in the near future.

Another form of conversion of electricity into chemical energy is the production of hydrogen or hydrogen products, which is becoming one of the main directions for energy sector development. At the end of 2021, the EU allocated funds in the amount of over EUR 500 billion for the development of projects for the use of hydrogen, which should be spent by 2030. Currently, the number of end-users who can produce hydrogen is limited to business entities that produce technical gases, but the goal of EU is to increase the use of hydrogen, primarily for transportation purposes. With adequate hydrogen tanks and hydrogen production facilities reaching a consumption change gradient of 10%/s, hydrogen production in the near future may become a significant resource for virtual power plants, for both balancing services and economic dispatch. The manifest problem of hydrogen storage is currently being solved in two directions, by obtaining methanol or ammonia.

Converting electrical energy into potential energy for end-consumers is also promising from the point of view of VPP. The end-users who perform this energy conversion are primarily public utility companies of waterworks and sewerage. Technological processes of water supply and sewerage removal involve processes of water pumping from or into water/sewerage storage areas and usually have a certain freedom regarding accumulation (reservoir) level. As such, they represent a significant potential for the aggregation of manageable consumption, especially from the point of view of grouping the end-users who are aggregated. It is not necessary to wait for the near or far future to develop resources for this type of consumption since they are already available now.

2.2.1 Energy sources. The most important energy sources of PS end-users, which are prospective for aggregation into virtual power plants, can be divided into groups according to manageability:

- Unmanageable energy sources:
  - solar panels,
  - solar collectors,
  - solar thermal panels (cooling of these panels warms up the water);
- Manageable energy sources, the application of which can be optimized (economic dispatch):
  - biomass and biogas (thermal energy),
  - fossil fuels (thermal energy),
  - heat pumps (source of thermal energy),
  - unmanageable sources with energy storage;
- Combined energy sources, the most promising from the point of view of the application in virtual power plant applications, with a significant number of variable states that need to be monitored:
  - cogeneration (they are mainly used by business entities whose production process requires the use of both electricity and thermal energy, possibly of the process steam, as well),
  - heat pumps in combination with heat storages (sources of thermal energy, the application of which increases the capacity of thermal storages),
  - low-temperature sources of thermal energy (sources that are under significant development, a combination of heat pumps and waste heat from industrial processes or heat generated by cooling the computer centers).

2.2.2 Manageable consumption and storing of energy. PS end-users' energy storages that are currently in use correspond to already mentioned forms of electricity transformation into another type of energy. Thermal energy storages (heat accumulators), chemical energy storages (mainly batteries), and energy storages in which electricity is stored as potential energy are the most common. Considering that they are currently widely available and that it is not necessary to wait for their development, only heat accumulators and potential energy storage will be considered in this article. Heat accumulators can be targeted, and the thermal capacities of other objects can be used as heat accumulators (for example the walls of the heated space). Manageable consumption in combination with energy storages expands the range of services that virtual power plant can provide to the system - system balancing and economic dispatch.

The concept of consumption management as a support for frequency regulation was mentioned more than forty years ago, [29], where in addition to the concept of "production follows consumption", the concept of "consumption follows production" was shown. In [29], a categorization was made into passive and active consumption management. Passive consumption management mainly refers to loads that naturally use the duty cycle and can be turned on/off temporarily without compromising the duty cycle and user's comfort. As the first candidates for manageable consumption, which do not require additional investments other than management, thermostatically controlled devices stand out, which inherently have thermal energy storing, and at the same time are large consumers in households as end-users, [30]. Such devices include air conditioners, electric water heaters, storage heaters, etc. In [29], authors presented possibilities for the use of a device that, based on the frequency measurement of the network to which it is connected, can turn on/off certain consumers. However, at that time there was no available infrastructure and technology that could support the rapid flow, storing, and processing of large amounts of information.

With the application of new technologies to old ideas, in [31] a prototype of remotely controlled switch of an electric water heater, based on the IIoT concept, with the possibility of reading the values from sensors measuring the water temperature, the consumption current and the network frequency is presented. In [31], statistical analysis of the operation of the electric water heater was performed and available changes in its power and energy were estimated - increases and decreases, depending on the current needs of the PS, but also on the expected customer requirements. Based on the obtained statistical indicators, a dynamic model of a large number of water heaters that are used in a similar way - a dynamic model of one cluster - was proposed. By analysing the possibility of working in secondary frequency regulation, it was shown that such system can achieve even better results in terms of response time, relieve the existing, conventional generation units and contribute to the stability of PS and the safe supply of customers. In addition to technical analyses, in [31], a simplified economic analysis of one such project was performed. It was pointed out that the investment would be returned to the user in about five months, and that the rate of annual income in the first year is approx. 270%.

Heat accumulators, as targeted energy storages, represent one of the cheapest forms of energy storage, with a price of less than 15 USD/kWh, [32], while according to [33], the price of large heat storages may range 15-50 EUR/m^3. Inexpensive heat accumulators most often accumulate the heat in water, and accumulators of 50 litres of water, up to seasonal heat accumulators with the capacity of over 500,000 m^3 of water, are in use [34]. In combination with a heat pump, which lowers the lower limit of usable water temperature to below 20 ^oC, heat accumulators represent an extremely elastic plant from the point of view of manageability of consumption.

If the thermal storage is zoned as to have two separate storages, the energy from warmer storage can be used directly for heating the space when the price of electricity is high, and in case of a favourable electricity price, the heat from colder storage can be used for heating the space after conversion via a heat pump. Heat sources are mainly solar collectors (as in Figures 1 and 3), but also waste heat from cogeneration or even the conversion of electricity into thermal energy. Large thermal energy storages can reach a capacity of over 40 GWh individually. In the areas where 27% of the final energy is spent on heating the space [26], they can represent an ideal solution for the annual balancing of V-RES electricity generation. Energy losses of seasonal thermal energy storages can be reduced by up to 10%.

Manageable consumption with storing the energy in the form of potential energy is present in technological processes in which the fluid is transferred from one place to another at a higher altitude. Examples of end-consumers of electricity that perform the described energy conversion are public utility companies of water supply and sewerage. In plain areas, it is common to maintain the water pressure in the water supply system by pumping the water into a water tower, the highest point of the settlement. A water tower is a water reservoir having a level gauge, with a maximum and minimum allowed value. Depending on the water consumption, the pumps of the water supply systems are manageable on an hourly basis, and the manageability depends on permitted minimum and maximum volumes of the water in the water tower. Sewage systems have collectors that also have permitted levels and pumps that are manageable, as in the case of water supply.

3. MANNERS OF AGGREGATION OF PRODUCTION AND CONSUMPTION

3.1 Active manner of aggregation – EPS as a possible Aggregator

Since EPS, among other things, performs the roles of electricity producer, trader, and supplier, during the optimization of the entire portfolio of EPS, different types of plans are made, for several time horizons. When creating medium-term (quarterly, monthly, and weekly) and short-term (day-ahead and intraday) electricity generation and trade plans, the goal is to optimize their production by making maximum use of the flexibility of power plants, so that the company achieves the highest possible profit. To achieve this, it is necessary to place the largest possible part of available energy in periods of the highest market prices, taking into account already contracted obligations/deliveries (supply and previously concluded trade contracts) and existing constraints (primarily technical characteristics of power plants, as well as maximum and minimum levels of reservoirs, and coal landfills). This is achieved by electricity trading so that in periods of low market prices power plants are "pushed" to technical or biological minimums, while the difference between demand (consumption) and production is compensated by purchases on the "spot" market, in which way most of the primary energy (coal, water) is transferred to periods of high prices. In this sense, in order to transfer as much of the primary energy as possible from the period of low to the period of high prices, it is necessary for the power plants to have as wide range as possible between nominal power and technical (or biological) minimums, i.e., to have as much flexibility as possible.

On the other hand, the same effect can be achieved by using the available range of manageable consumption, that is, by "shifting" a part of consumption from periods of higher prices to periods of lower prices (Demand Side Management - DSM). Nevertheless, the possibility of applying DSM is quite limited, because there is a relatively small number of large industrial/commercial consumers (customers) of electricity to whom their production process allows consumption management and where the cost of electricity represents a significant share in the price of final product (energy-intensive customers), so that they could be motivated by adequate price signals. Otherwise, there is a relatively large number of small customers and households where "shifting" of consumption is possible, but there is no adequate regulation, infrastructure, or price signals to enable it, yet. In addition, more significant effects of manageable consumption can only be achieved by aggregation (consolidation, grouping) of a large number of (mostly smaller) end-users of PS, which is one of the main reasons for the introduction of a new participant in the electricity market – the Aggregator.

The Aggregator can also consolidate smaller, distributed (dispersed) electricity producers, and most often those with controllable production, such as the example of a prosumer with the possibility of electricity storing, illustrated in Figure 3. It shows an energy "smart" house, as well as a radially fed distribution network to which a number of such, spatially distributed, houses are connected. From the perspective of consumers and "local green generation", the edge concept is presented, the main advantages of which are short data processing time (delay reduction) and simpler local production and consumption process management. Figure 3 shows a general case – a household that can produce and store both thermal energy and electricity. The aggregator can consolidate even fewer complex cases, as in [31].

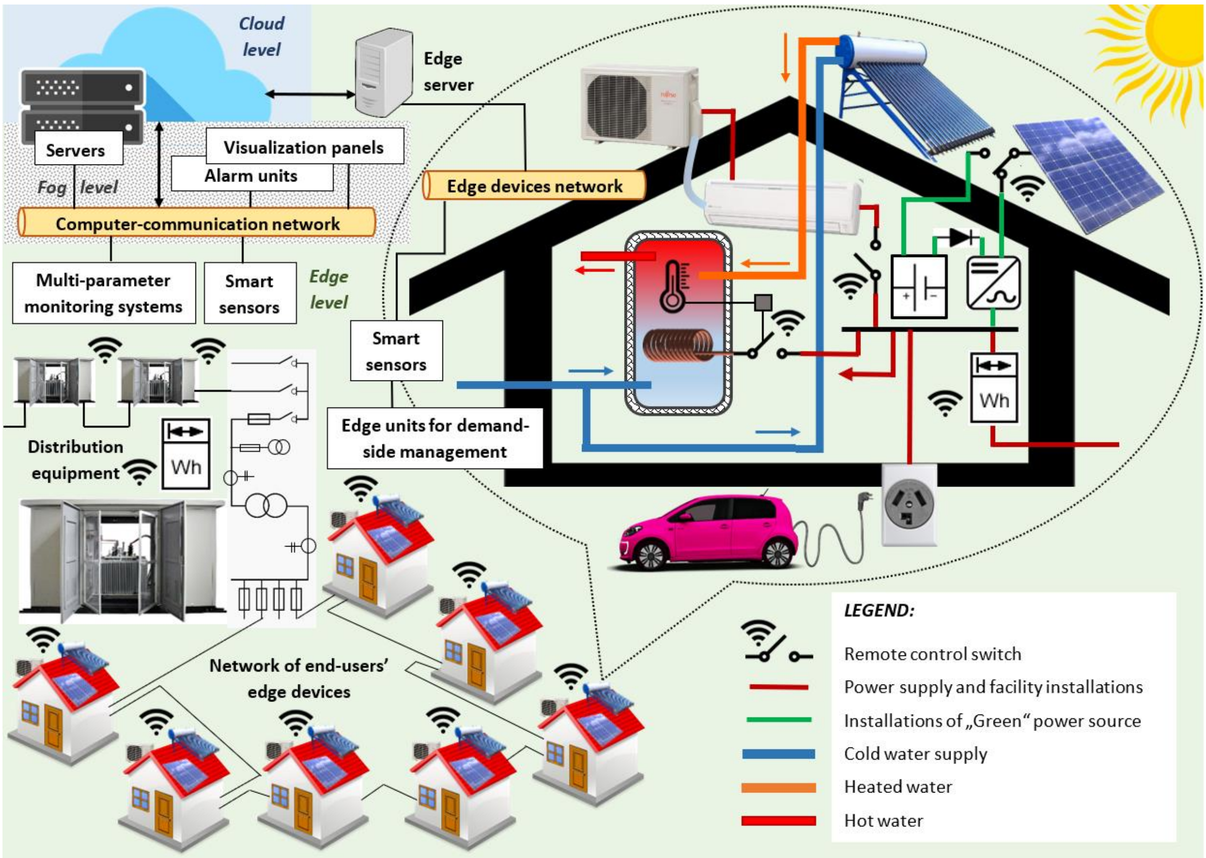


Figure 3 A hybrid IIoT concept for composite virtual power plant aggregation and management

The aim is to provide as much flexibility as possible which Aggregator valorise subsequently on the electricity market. Depending on technical possibilities that the Aggregator disposes of within its portfolio, beside shifting of consumption/production, the latter realizes revenues from flexibility and on the markets of system services and balance energy. Accordingly, Aggregator makes a profit by offering its services (flexibility) to various interested parties (market participants):

- to other producers/suppliers for whom the flexibility is important for production/supply portfolio optimization, as well as for balance responsibility on the balance energy market,
- to transmission system operator, through system services (provision of secondary and tertiary reserve power), indirectly reducing the required level of reserve at the production side (and thus opportunity costs of production),

- to distribution system operator, bearing in mind the fact that due to the increasing number of connections of V-RES to distribution network there is a need for flexibility for the purpose of efficient and safe distribution network management, as well as possible investment costs reduction (in distribution network).

Taking into account the volume of EPS portfolio, business it performs, as well as potentials that the role of Aggregator brings along, a clear interest of EPS is to perform this role in order to complete the possibilities of portfolio of EPS and provide additional source of revenues. Considering the electricity supply function within EPS, and that, in [2], the possibility that, beside independent aggregators, suppliers also deal with aggregation in electricity market is reviewed, one of the options that should be explored in terms of feasibility is to register "EPS Snabdevanje" (EPS Supply) as Aggregator, as well.

In this regard, the business activities of a similar state-owned enterprise like GEN-I could serve as an exemplar. The above company plays the role of an aggregator-supplier in more than one country in central-eastern Europe. As far as aggregation is concerned, GEN-I also disposes of manageable consumption and distributed generation, as well. Their virtual power plant concept is based on development of unique platform consolidating aggregator portfolio management, access to different markets, e-mobility and advanced analytics. Such concept enables GEN-I to participate in an active manner in providing balancing services in Slovenia and Austria from virtual power plant, [35].

3.2 Passive manner of aggregation – dynamic pricing

Dynamic pricing, option usually offered by traditional electricity suppliers, is a type of supply contract containing variable part of price that partly or completely reflects price fluctuation on the wholesale electricity market. With such contract form, buyers are encouraged to react on price signals from the market and adjust their consumption according to price changes (i.e., tend to reduce electricity consumption during high price rate hours and to increase it during low price rate hours). This type of proactive approach of buyers may lead to electricity bill savings. However, it should be highlighted that such approach bears certain risks regarding sudden exposure to high prices in particular periods. Therefore, it is very important that the buyer is highly acquainted with all aspects and risks, review well possibility of managing own consumption and even maybe negotiate such contract that will contain some limitations that would protect him from sudden price change and its volatility in the short term.

Some of the examples of dynamic pricing from European practice, [36], are described below:

- *Octopus* supplier (Great Britain): offers a tariff named "A*gile*" with electricity price for customer changing each 30 minutes. On the website of the supplier, interactive presentation of exemplary buyer for whom such form of pricing is the most applicable is offered and a review and comparison with other static tariffs the supplier may offer are presented. Contract contains the limitation clause ("*price cap*"), i.e., the clause on the highest price that the customer may be exposed to.
- *easyEnergy* supplier (Netherlands): offers a tariff reflecting the price for end user as combination of variable part (hourly wholesale price) and fixed part (fixed fee defined on a monthly basis). There is no protection or alarm for the buyer that would indicate the high prices and hence sudden increase in electricity bill.

4. TECHNICAL AND ECONOMIC FEASIBILITY OF VPP IMPLEMENTATION

There are relatively small number of large industrial (commercial) electricity customers in Serbia to whom the generation process would allow consumption management and the electricity cost has a significant share in the price of final product. These are energy intensive customers that might be motivated by adequate price signals. The recent increase in electricity price for commercial customers further increased its share in final product for a large number of energy intensive customers, so that the interest of commercial customers in participating in possible consumption management programs should be examined.

Otherwise, there is relatively large number of small customers and households who have possibility of consumption "shifting" but without adequate infrastructure for implementation so far (for example "smart" meters, remotely controllable switches, etc.). Besides, the price for guaranteed supply is still significantly lower than the market price, thus there are relatively rare periods with possibility of motivating the households and small customers to change the manner and time of use of their electrical appliances. Namely, it is rare that the market price is lower than the price for guaranteed supply.

Due to the above mentioned reasons, and above all due to the lacking regulations (see Chapter 5) and actual inability for assets management related to the assets that does not belong to EPS (such as storage water heaters in example from [31]), EPS in the capacity of a supplier exclusively (when it comes to consumption) cannot make any savings on the account of the existing customers that it could have as an aggregator of a VPP and after providing technical conditions for such active approach. Cost estimation and estimation of possible benefits from VPP establishment is given in this chapter, but only for the component of manageable consumption based on remote controlled preparation of sanitary hot water.

4.1 VPP implementation costs – estimated costs of required hardware and software resources

Depending on the type of switches and a number of sensors (symbolically presented on the Figures 1 and 3, as far as manageable consumption is concerned), price of IIoT devices for acquisition with remote switch, with installation, amounts to 50÷300 EUR per consumer/switch. Total price per consumer depends on number and type of devices of an entity (for example household). Funds are also needed for the purchase or rent of server, as well as for software maintenance and development. Depending on the complexity and expected number of users, funds for software development are estimated in the range of 300,000 – 1,000,000 EUR. For the range of 10,000 – 100,000 users, software maintenance and server lease costs would be 30,000 – 60,000 EUR/year. Investment and exploitation cost estimation for 10,000 users, corresponding to the framework range of one 50 MW composite VPP are presented in Table I. It is important to notice that software development costs practically do not depend on number of users, thus their percentual share decreases as the number of users increases.

Table I Cost estimation for 50 MW VPP

10,000 users	cost	amount
CAPEX (EUR)	IIoT devices	1,000,000
	software development	500,000
	total CAPEX	1,500,000
OPEX (EUR/y)	server	40,000
	personnel costs	40,000
	total OPEX	80,000

4.2 Market opportunities for using virtual power plant and examples of benefits

Greater flexibility on the side of electricity consumption and distributed production, aggregated and managed through the virtual power plant concept, can lead to numerous benefits in terms of efficiency and operating costs of PS. The virtual power plant operator, depending on technical characteristics and the possibility of aggregated production and consumption, can use it for trading and optimizing its own portfolio on the wholesale market, as well as for providing the system services to transmission and distribution system operators.

In this context, the market value of a virtual power plant consisting of 50 MW of aggregated flexible consumption, managed by an independent aggregator, was considered as an example of the effects of introducing the virtual power plant concept. It is important to note that the mentioned 50 MW refer to the equivalent flexible part of consumption from the total consumer portfolio, which will be available and which the aggregator optimizes on the market. A proper assessment of this level of available flexible capacity to create a VPP offer is very important. Should the aggregator make a wrong assessment, i.e., overestimate the level of available flexible part of portfolio, it will be exposed to a higher financial risk in case of inability to provide the contracted services (for example imbalance on balancing market, penalties for not adequate level of reserve, etc.). Flexibility of aggregated consumption is presented through the option of possibility of intra-day "shifting" ("*Load Shifting*") up to the maximum of 4-hour duration. The described virtual power plant is modelled in commercial software tool for energy market simulations, PLEXOS, and optimized as market participant according to market conditions in Serbia recorded in 2021 (hourly profile of wholesale prices from SEEPEX, [37]). This optimization is illustrated under the Figure 4. Potential revenues for Aggregator that may be realized on wholesale market have been reviewed without considering further services that the virtual power plant could possibly provide. Such revenues are shown in Table II.

Table II Potential revenues of Aggregator for example of 50 MW VPP optimization, as per the Figure 4

Indicator	Unit	Value
Energy offtake	GWh/y	72.8
Delivered energy	GWh/y	72.8
Average purchase price	EUR/MWh	79.8
Average selling price	EUR/MWh	144.74
Average market price	EUR/MWh	114.02
Expenses for purchased energy	MEUR/y	5.80
Energy sales income	MEUR/y	10.54
Market profit	**MEUR/y**	**4.74**

The goal of the analysed example is to illustrate the market needs for sources of flexibility, i.e., possible income for one form of use of virtual power plant. Based on the conducted analysis (Figure 4, Table II), it can be concluded that there is a significant potential in terms of economic income from the virtual power plant management.

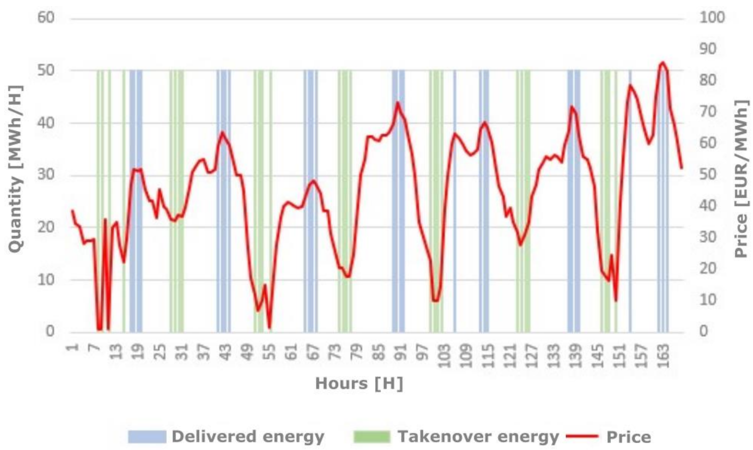


Figure 4 Example of 50 MW VPP optimization on the wholesale electricity market, on a week sample basis

We emphasize that for each potential business case of implementing a virtual power plant, it is necessary to analyse the costs and benefits in detail, i.e., to conduct a complete technological and economic analysis with an sensitivity analysis of the results to the changes in input parameters. This is especially important considering the last energy crisis and the enormous increase in electricity market prices (in this regard, it should be noted that the average prices in Table II are lower than those that occurred in the meantime).

It should be also emphasized that a prerequisite for the effective implementation of aggregation is the existence of a legal-regulatory framework with removed barriers for the appearance of aggregators in different markets, especially in terms of providing auxiliary services to transmission and distribution system operators. Namely, the profitability of implementation of such a concept will largely depend on adequate valuation of these services.

5. LEGAL FRAMEWORK AND CURRENT LIMITATIONS IN SERBIA

Amendments to the Energy Law (Official Gazette of RS, no. 40/2021, hereinafter referred to as: EL) introduce new electricity market participant – Aggregator, but its role, the same as its rights and obligations in the electricity market, has not been fully defined and elaborated in secondary legislation yet. Notion of aggregation is defined by Article 2 of EL as "*aggregation of electricity consumption and/or generation for the purpose of purchasing, selling or auctioning on electricity markets*", while Aggregator as one of the electricity market participants is defined as "*legal entity or natural person that provides the service of aggregating electricity consumption and/or generation for further sale, purchase or auctions in electricity markets*". The role of Aggregator is defined by Article 210b of EL as follows: "*Aggregator acts in electricity market on behalf and for the account of market participants for whom it provides the service of aggregating electricity consumption and/or generation*", and it shall:

1) act toward the market participant in a non-discriminatory manner;
2) publish the general conditions of the offer for contract conclusion, i.e., to inform market participants in a convenient way about the offered conditions;
3) provide all relevant data to the market participant free of charge at least once during the accounting period if the market participant requests it;
4) inform market participants about the aggregation function on its website or in any other convenient way.

Aggregators and market participants conclude contracts regulating mutual relations (see Figure 1, above).

Law on the Use of Renewable Energy Sources (Official Gazette of RS, no. 40/21, hereinafter referred to as: LoURES) indirectly also provides for an aggregator and a role of aggregator; Article 58 of LoURES defines that "*prosumer is entitled to <u>independently or by means of an aggregator</u> generate electricity for own consumption, store the electricity for own needs, deliver surpluses of generated electricity into transmission, distribution and/or closed distribution systems and may not use incentive measures in the form of market premium or fid-in tariffs, nor may it be entitled to guarantees of origin.*" Article 66 of LoURES also defines that "*aggregation of renewable energy sources, and/or legal entity established on a principle of open and voluntary participation of its members*"… "*has right of production, consumption, storage and sale of renewable energy and right of access to all energy markets, <u>directly or by means of an aggregator</u>, in a non-discriminatory manner, as well as other rights and obligations of producers under this law.*"

Although the above mentioned laws regulating energy sector in the Republic of Serbia foresee an aggregator as a market participant/system user and define aggregation activity, legal regulations in this part have not been fully completed. In particular, the fact that aggregation is not intended to be an energy activity must be taken into account, and therefore the aggregator (natural or legal entity that provides the service of consolidating electricity consumption and/or generation for resale, purchase or auctions in electricity markets) cannot obtain a license or other consent to provide this service.

Therefore, to further define the role of aggregator, it is necessary to amend national secondary legislation in accordance with the "Clean Energy Package" of the European Union, which entered into force in June 2019, and the guidelines from the *EU Directive 2019/944*. This package defines new participants in the market such as aggregators, i.e., independent aggregators, and more precisely defined energy activities such as aggregating and energy storing. According to the Directive, in general, each electricity market participant is obliged to regulate his balancing responsibility by contract; to transfer it to another electricity market participant, to sign a full supply contract or to register as a balance responsible party. By Article 17(3.d) of this Directive, not even the new market participant – the Aggregator is exempt from this obligation. In this sense, there is no essential difference between the Supplier and the Aggregator. Nevertheless, one of the main differences between these two market participants is that the Supplier manages consumption implicitly (the customer reacts to the Supplier's price signals from the bill, and the tendency is to move towards dynamic pricing with the introduction of "smart" meters), while the Aggregator has the ability to manage consumption explicitly (directly, actively). This should include defining/contracting the conditions under which the Aggregator manages the customer's consumption and at what price, within an individual contract or within the Supply Agreement. Consumption explicit management would enable the Aggregator to make a profit on the markets of system services and balance energy, but it requires, in addition to currently lacking regulations, adequate infrastructure which implies the mass use of appropriate "smart" meters, which is another obstacle that needs to be eliminated to fully implement the concept of Aggregator on the market of the Republic of Serbia.

Additional limitation and possible problem, primarily in regulating the relationship between Aggregator and DSO, is represented by the legislative provision that the management of renewable sources over 160 kW is responsibility of DSO, "Elektrodistribucija Srbije" (EDS).

The position of the authors of this article is that EDS should operate RES power plants of individual capacities higher than 160 kW only to ensure safe operation of the distribution system. In such terms, Aggregator should dispatch and control these assets, while EDS would have a possibility to change their power (including power curtailment) only when safety of the distribution system is endangered (so-called "*Re-dispatching*" – a measure of change in generation and/or consumption implemented by the system operator, changing physical power flows in the system to ensure the safety of the system and eliminate congestion in the system. Assets (RES power plants, manageable consumption, storages) re-dispatched by EDS (due to threatened system safety), should be financially compensated for the lost profit.

Practically, operating RES power plants of individual capacities higher than 160 kW by DSO (EDS) should be regulated based on similar technical and market principles as those when TSO (in Serbia: EMS JSC) operates power plants of higher capacities connected to the transmission system in the moments of compromised system safety.

6. CONCLUSION

On the side of end-users of PS, there is significant capacity in manageable consumption. With dispersed (distributed) electricity generation and its expected expansion, including "prosumers" that were put under legal framework in Serbia in 2021, the need, but also the interest, to effectively and efficiently manage consumption and generation will strengthen at the users' level. When you add to that the necessity of improving energy efficiency on the consumption side, as well as the fact that perhaps the greatest potential – both for savings and for manageability and flexibility – lies in water and space heating devices, the concept of aggregation into a multi-energy composite (cooperative, collaborative) virtual power plant is imposed as a possible solution. Investing in its creation, development, technical implementation and expansion can turn out to be a more favourable solution than investing in dilapidated thermal energy capacities whose production is based on low-caloric and less environmentally acceptable lignite. In this regard, the composite virtual power plant can facilitate the expected greater scope of V-RES integration and actually represents a replacement capacity in the PS of Serbia.

For the realization of a virtual power plant, it is first necessary to define a methodology based on which the technical conditions of manageability would be evaluated for end-users who want to be a part of the virtual power plant. The methodology would have to include an assessment of availability of the end-user's manageable consumption, storage and reserve capacities, as well as the maximum active power of the storage. A large number of end-users who would be involved in the realization of virtual power plant, would generate large administrative costs. Larger storages should be used primarily. First of all, it is necessary to take advantage of the manageability of significant users of PS. From the point of view of the utilization of storage capacities, the order in the strategy of investing in this component of the composite virtual power plant would be as follows:

- use existing thermal storages,
- use existing potential energy stores,
- investing in new thermal storages,
- when all options for the construction and application of thermal storages have been exhausted, include the battery-based and hydrogen-based storages in the implementation project.

It is clear that one of the prerequisites for the realization of virtual power plant is the application of modern, "smart" devices, such as remotely controlled switches, followed by the application of appropriate management and control software and appropriate protocols for two-way communication and data transmission. Regarding the complex structure of the virtual power plant system, the concept based on IIoT was evaluated as the most suitable to make an efficient system of control, data processing, management, and decision-making. Greater flexibility on the side of electricity consumption and distributed production, aggregated and managed through the concept of a virtual power plant designed in this way, can lead to numerous benefits in terms of efficiency and operating costs of PS.

Depending on technical characteristics and the possibility of aggregated generation and consumption, the Aggregator, i.e., the virtual power plant operator can use it for trading and optimizing its own portfolio on the wholesale market, as well as for providing the system services to transmission and distribution system operators.

It should be emphasized that a prerequisite for the effective implementation of aggregation is the existence of an appropriate legal-regulatory framework with removed barriers for the Aggregator's performance in various markets, including the market of ancillary services.

BIBLIOGRAPHY

[1] Belonogova N, Kaipia T, Lassila J, Partanen J, „Demand response: Conflict between distribution system operator and retailer", CIRED 21st International Conference on Electricity Distribution, Frankfurt, 2011, Paper No. 1085

[2] Vukovljak M, Janković M, „Novi učesnici na tržištu električne energije", 35. Savetovanje CIGRE Srbije, Zlatibor, 2021.

[3] Ropuszyńska-Surma E., Borgosz-Koczwara (Weglarz) M., „A virtual power plant as a cooperation network", *Marketing and Management of Innovations*, Issue 4, 2018, DOI: 10.21272/mmi.2018.4-13

[4] Adu-Kankam K. O, Camarinha-Matos L, „Towards Collaborative Virtual Power Plants", Chapter, *Technological Innovation for Resilient Systems*, pp 28-39, Advances in Information and Communication Technology, vol 521, Springer, January 2018, DOI: 10.1007/978-3-319-78574-5_3

[5] Adu-Kankam K. O, Camarinha-Matos L, „Towards collaborative Virtual Power Plants: Trends and convergence", Article, *Sustainable Energy, Grids and Networks*, Volume 16, December 2018, Pages 217-230, DOI: 10.1016/j.segan.2018.08.003

[6] Chen X., Yang G., Lv Y., Huang Z., „Power Management System Based on Virtual Power Plant", 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **356** 012006

[7] Przychodzień A., „Virtual power plants - types and development opportunities“, E3S Web of Conferences 137, 01044 (2019), RDPE 2019, https://doi.org/10.1051/e3sconf/201913701044
[8] Agbozo E., Masih A., „Virtual power plants: Powering smart cities of the future“, 18th International Multidisciplinary Scientific GeoConference SGEM 2017, DOI: 10.5593/sgem2018/4.1/S17.105
[9] Yavuz L., Önen A., Muyeen S.M., Kamwa I., „Transformation of Microgrid to Virtual Power Plant – A Comprehensive Review", IET Generation, Transmission and Distribution, January 2019, DOI: 10.1049/iet-gtd.2018.5649.
[10] Zhang J., „The Concept, Project and Current Status of Virtual Power Plant: A Review", 2022 J. Phys.: Conf. Ser. 2152 012059
[11] Gomes Makohin D. et al., "District Power Plant as a Virtual Power Plant Solution for Utilities", Conference Paper, June 2015, DOI: 10.1109/ISIE.2015.7281550
[12] Li S., Yu G., Zhou X., Xing N., "Research on New Urban Virtual Power Plant System", E3S Web of Conferences 248, 02004 (2021) CAES 2021, https://doi.org/10.1051/e3sconf/202124802004
[13] Mohanty S., Choppali U., Kougianos E., "Everything You Wanted To Know About Smart Cities: The Internet Of Things Is The Backbone", IEEE Consumer Electronics Magazine, vol: 5 (3), 2016, pp 60-70
[14] Tranchita C., "France Pilots Virtual Power Plant", Research, April 2016, DOI: 10.13140/RG.2.1.2296.6165, http://tdworld.com/grid-opt-smart-grid/france-pilots-virtual-power-plant
[15] EMoT, available at: https://navitasoft.com/en/news/what-is-energy-market-of-things (approached: November 2022.)
[16] Kankam O. Adu-Kankam and Luis M. Camarinha-Matos, "A Framework for Collaborative Virtual Power Plant Ecosystem", Chapter, in: *Collaborative Networks in Digitalization and Society 5.0. PRO-VE 2022*. IFIP Advances in Information and Communication Technology, vol 662. Springer, Cham., September 2022, https://doi.org/10.1007/978-3-031-14844-6_13
[17] Omelčenko, V., Kavanagh, R., "edgeFLEX Project – D3.3 Report on VPP Optimisation, V2 (WP3 – Optimisation of a VPP consisting of variable and dispatchable RES)", ALPIQ, March 31, 2022
[18] Zhang, Z., et al., "Optimization scheduling of virtual power plant with carbon capture and waste incineration considering P2G coordination", Energy Reports 8(5): 7200-7218, November 2022, DOI: 10.1016/j.egyr.2022.05.027
[19] Ju, L., et al., "Bi-level electricity–carbon collaborative transaction optimal model for the rural electricity retailers integrating distributed energy resources by virtual power plant", Energy Reports 8(95): 9871-9888, November 2022, DOI: 10.1016/j.egyr.2022.07.171
[20] Hongliang, W., Benjie, L., Daoxin, P., Ling, W., Jun, X., "Virtual Power Plant Participates in the Two-Level Decision-Making Optimization of Internal Purchase and Sale of Electricity and External Multi-Market", IEEE Access PP(99):1-1, September 2021, DOI: 10.1109/ACCESS.2021.3112549
[21] Milić S. D, Babić B. M, "Towards the Future - Upgrading Existing Remote Monitoring Concepts to IIoT Concepts", *IEEE Internet of Things Journal*, Electronic ISSN: 2327-4662, DOI: 10.1109/JIOT.2020.2999196, Vol. 7, Issue 12, December 2020, pp. 11693-11700.
[22] Milić S. D, Veinović S, Ponjavić M, "Industrial Internet of Things (IIoT) – Strategies and Concepts", XIX International Symposium Infoteh-Jahorina 2020, Proc., Vol.19, KST-4, Jahorina, Republic of Srpska, March 18-20, 2020, pp. 81-85.
[23] Milić S, Stojadinović G, Tomić N, "Prilagođenje postojećih sistema daljinskog nadzora IIoT konceptima sa hijerarhijski definisanim nivoima obrade podataka", CIGRE - Srbija 35. savetovanje, Zbornik radova, ISBN: 978-86-82317-84-5, rad R D2 - 09, 03 - 08. oktobar 2021. godine, Zlatibor, Srbija.
[24] Zhuang W. W, Morgan C, Nakamoto I, Jiang M, "Big Data Analytics in E-commerce for the U.S. and China Through Literature Reviewing", *Journal of Systems Science and Information* 9, no. 1 (2021): 16-44. https://doi.org/10.21078/JSSI-2021-016-29
[25] Kang C, Wang Y, Xue Y, Mu G, Liao R, "Big data analytics in China's electric power industry: modern information, communication technologies, and millions of smart meters", *IEEE Power and Energy Magazine*, *16*(3), pp.54-65, 2018.
[26] Fleiter T, Elsland R, Rehfeldt M, Steinbach J, Reiter U, Catenazzi G, et al., "Profile of heating and cooling demand in 2015". Heat Roadmap Europe Deliverable 3.1; 2017.
[27] Belarus energy profile, IEA, 2019.
[28] https://newsroom.porsche.com/en.html
[29] Schweppe F. C, Tabors R. D, Kirtley J. L, Outhred H. R, Pickel F. H, Cox A. J, „Homeostatic utility control“, *IEEE Transactions on Power Apparatus and Systems*, 1980, https://doi.org/10.1109/TPAS.1980.319745
[30] Tindemans S. H, Trovato V, Strbac G, „Decentralized Control of Thermostatic Loads for Flexible Demand Response“, *IEEE Transactions on Control Systems Technology*, 2015; 23. https://doi.org/10.1109/TCST.2014.2381163.
[31] Georgijević N, Vlaisavljević D, Šiljkut V, Misović D, Milić S, „Primena koncepta „Industrijski internet stvari“ na primeru upravljivog električnog bojlera kao potrošača i analiza mogućnosti u regulaciji učestanosti“, 35. Savetovanje CIGRE Srbije, Zlatibor, 2021.
[32] Kuravi S, Goswami Y, Stefanakos E. K, Ram M, Jotshi C, Pendyala S, Trahan J, Sridharan P, Rahman M, Krakow B, "Thermal energy storage for concentrating solar power plants", *Technology and*

Innovation, Vol. 14, pp. 81–91, 2012, DOI: http://dx.doi.org/10.3727/194982412X13462021397570

[33] IEA-SHC TECH SHEET 45.B.3.2, Seasonal pit heat storages - Guidelines for materials &construction December 2014

[34] Bertelsen N, Petersen U. R, "Thermal Energy Storage in Greater Copenhagen", Master thesis, Aalborg University Copenhagen, 2017.

[35] Lacko R., "Unlocking the aggregation in regional markets Practical experience & best practice (aggregator's perspective)", Energy Community Workshop, 2022

[36] BEUC, Flexible Electricity Contracts Report, April 2019

[37] ENTSO-E Transparency Platform, https://transparency.entsoe.eu/

BIOGRAPHIES

Vladimir M. Šiljkut was born in Belgrade in 1966. He graduated in 1994 and received his doctorate in 2015 at the Faculty of Electrical Engineering in Belgrade. He worked in "Elektrodistribucija Beograd" (1995-2013) on distribution network planning, development and exploring, he led the Laboratory for Electricity Meters and Center for Integrated Management System. In "Electric Power Industry of Serbia", he headed the Department for Trade and Relations with Tariff Customers (2013-2015). Further, (2015/16) he managed and coordinated projects on reducing the Distribution System Operator losses. From 2016 to 2022, he had been, and currently is, the Head of the Unit for preparation of new investments in power plants and renewable energy sources. From March 2022 to July 2023 he was the Advisor for business system to EPS General Manager. Over a period of more than a decade, he had been engaged as visiting lecturer for electricity distribution and retail and power plants and switchgears at the School of Electrical and Computer Engineering in Belgrade. He is a (co)author of more than 75 articles and papers (four articles in international journals), published and presented during numerous national, regional and international conferences. These papers' scope includes the load forecasting method, optimal network planning, electricity losses estimation, RES, load management, power transformers, metrology, etc. He is also a co-author of one practical book on electric power distribution and electricity retail, in Serbian. As a member of Serbian National Committee of CIRED, and its Executive Board, he is particularly engaged in the session 1 – Network Components (as a Chairman), session 2 – Electricity Quality (a member) and session 5 – Distribution Network Planning.

Nikola Georgijević was born in 1987 in Belgrade. After completion of his undergraduate studies, he obtained master's and doctorate diplomas in Electrical Engineering and Computing in 2011 and 2020 respectively, at the Faculty of Electrical Engineering in Belgrade. He worked in Nikola Tesla Institute (2011-2020), where he was engaged in exploring EES analysis and optimization. Since 2020, he has been employed in Electricity Coordinating Center as chief of the software development section. His fields of interest are computer programming, mathematical modelling, EES stability optimization and analysis, machine learning, and artificial intelligence. He managed and participated in technical projects in the regions of south-east Europe, the Near East, Africa, and South America.

Saša Milić was born on 11th July 1967 in Belgrade. He graduated in 1993 and received his master degree and doctorate in 2000 and 2008, respectively, at the Faculty of Electrical Engineering in Belgrade. He has been a science adviser since 2021. His areas of interests and fields of professional expertise are: electrical and magnetic measuring, laser measuring, laser technics, optoelectronics and infrared technics, fuzzy logic, machine learning and artificial intelligence, internet of things and industrial internet of things, risk analysis and assessment, development strategies and management and decision-making algorithms, monitoring systems and expert systems. He was the project manager in more than one science, expert and innovative projects. He published over 100 scientific papers in the country and abroad. He published 10 technical solutions and had several technical and scientific lectures in prominent scientific institutions. Since 1994, employed in Belgrade University Electrical Engineering Institute Nikola Tesla. He is a member of scientific and technical boards of conferences and magazines.

Aleksandar Latinović was born on 6th September 1986 in Bihać. He went to Zrenjanin gymnasium, then graduated and received master degree at the Faculty of Electrical Engineering, Energy Department, in Belgrade. He has been employed in EPS since 2010. Special interests of his are within the field of ancillary services in electric power industry, primarily turbine governors, and additionally digitalization in electric power industry as well as technical and legal regulations in the field of energy. During the period of education, he obtained the following success: the best student in his generation both in primary and secondary school, awards on local and national competitions in physics, awards on knowledge competition of "Elektrijada" and an average mark obtained during bachelor and master studies of 9,5. Employed in EPS, Aleksandar participated in several projects on development of the turbine governors implemented in EPS, and development of thermal power plants simulator.

Projects on improving technical quality of ancillary services and one of the largest digitalization projects in the Republic of Serbia, PROTIS project, are some of the projects he directly managed.

Dušan Vlaisavljević was born in 1988 in Belgrade.Graduated in 2012 as Master in Electrical Engineering and Computer Science from Faculty of Electrical Engineering, University of Belgrade. The main areas of professional engagement include electricity market modelling and analysis, power generation portfolio optimization, power system development planning, development of wholesale and balancing market mechanisms and procedures, as well cost-benefit and economic evaluations of power plants and transmission infrastructure projects. He was engaged in numerous regional and international projects for power utilities, transmission system operators and international institutions (World Bank, European Commission, USAID and Energy Community Secretariat) in regions of South East Europe, Central East & Central West Europe, Black Sea region, South Caucasus, South East Asia and Central Asia.

Radoš Čabarkapa was born on 1st May 1986 in Belgrade. He completed primary school "Petar Petrović Njegoš" as a holder of the diploma of Vuk Stefanović Karadzić and the best student in his generation. In the period from 2001 to 2005, he is a student of the Mathematical Gymnasium in Belgrade. Afterward, in 2005, he enrolls in electrical engineering studies at the Faculty of Electrical Engineering (electric power systems department) in Belgrade. He completed the above mentioned studies in 2009 and master studies at the same Faculty in 2012. Since 1st June 2010, he has been employed in the public enterprise Electric Power Industry of Serbia occupying different positions in Electricity Trading Department, and currently in the same company, he heads the section for support to the planning and analysis of the plan implementation in the Power Portfolio Management Affairs. Areas of interest and professional expertise are focused on electricity market analysis, software modeling in the energy field and challenges of RES transition. As a member of working groups of the Ministry of Mining and Energy, he participated in development of strategic documents, by-laws and Law on the use of Renewable Energy Sources.

UDK: 620.9:502.131.1(497.11)
620.9:005.21(497.11)

Vladimir M. Šiljkut[1], Nikola Georgijević[2], Saša Milić[3],
Aleksandar Latinović[1], Dušan Vlaisavljević[2], Radoš Čabarkapa[1]

Agregacija kompozitne virtuelne elektrane – mogućnosti i ograničenja za primenu u Srbiji

[1] Akcionarsko društvo „Elektroprivreda Srbije“, Beograd, Srbija[1]
[2] Elektroenergetski koordinacioni centar, Beograd, Srbija
[3] Elektrotehnički institut „Nikola Tesla“, Beograd, Srbija

Kategorija rada: Pregledni članak

Ključne poruke

- Dat detaljni prikaz literature o virtuelnim elektranama, pregled koncepata i konkretnih rešenja
- Sagledani izvori energije, načini agregacije i tehnički potencijal za uspostavljanje virtuelne elektrane
- Predložen koncept kompozitne virtuelne elektrane, procenjeni troškovi, koristi, zakonska ograničenja

Kratak sadržaj

Elektroenergetski sektor Srbije se sve više suočava s izazovima budućnosti. Većina proizvodnje električne energije zasniva se na niskokaloričnom lignitu. Njegov sve lošiji kvalitet uzrokuje pad nivoa sigurnosti, pouzdanosti i efikasnosti termoelektrana, uz povećanje zagađenja. Osim značajnih sredstava namenjenih njihovoj revitalizaciji, velika su ulaganja u nove, skupe sisteme za smanjenje emisija štetnih materija. Uz najavljene ugljenične takse, čiji se rast očekuje u budućnosti, isplativost ovih izvora i tržišna konkurentnost cene električne energije dobijene iz njih, postaju krajnje upitni i neizvesni. U procesu neminovne dekarbonizacije, postavlja se i strateško pitanje pred srpske eksperte – čime nadomestiti znatne bazne (termo)kapacitete, koji će verovatno biti ugašeni?

Na drugom kraju sistema, problem predstavljaju neefikasno korišćenje električne energije, neprihvatljivo visok nivo njenih gubitaka, uključujući i one usled njenog neovlašćenog korišćenja. Pri tome, ni iz bliza nisu iskorišćene tehničke mogućnosti za upravljanje opterećenjem niti za primenu većeg broja tarifnih stavova, radi željenog odziva potrošnje.

U takvim okolnostima, ključno je pitanje – kakvu strategiju investiranja treba odabrati? Ovaj rad predlaže rešenje koje bi imalo pozitivan uticaj na oba kraja sistema i njegove aktere, ali i na mreže između njih i njihove operatore. „Elektroprivreda Srbije“ bi mogla da iskoristi najavljeno uvođenje agregatora, kao novog učesnika na tržištu električne energije, za svojevrsni zajednički poduhvat sa krajnjim korisnicima, za uspostavljanje kompozitne virtuelne elektrane. Ona bi za elektroprivredu predstavljala novi, zamenski kapacitet, a za kupce izvor ušteda i potencijalnog prihoda. Ovakva elektrana bi obuhvatila različite, dispergovane obnovljive izvore, kako električne energije, tako i toplotne, sisteme za skladištenje energije, punjače za električna vozila, upravljivo opterećenje kupaca i različite programe za odziv potrošnje. Povećanjem obima ovakve agregacije, kompozitna virtuelna elektrana bi agregatoru takođe omogućila pružanje pomoćnih sistemskih usluga operatoru prenosnog sistema, što bi predstavljalo dodatni benefit. U sinergiji s drugim neophodnim, strateškim koracima, predloženi koncept bi Srbiji mogao da obezbedi sigurniju energetsku budućnost.

Ključne reči

Agregacija, dekarbonizacija, distribuirana proizvodnja, pomoćne usluge, odziv potrošnje, upravljanje opterećenjem, virtuelna elektrana

Primljeno: 7. april 2023. Recenzirano: 9. maj 2023.
Izmenjeno: 16. maj 2023. Odobreno: 25. maj 2023.
[1]Korespondirajući autor: Vladimir M. Šiljkut
Tel. +381-64-897-46-72 E - mail: vladimir.siljkut@eps.rs

Napomena:
Članak predstavlja proširenu, unapređenu i dodatno recenziranu verziju rada „*Agregacija kompozitne virtuelne elektrane – jedan od mogućih odgovora na izazove za elektroenergetski sistem srbije u procesu dekarbonizacije*“, nagrađenog u Stručnoj komisiji STK-5 *Planiranje distributivnih sistema* na 13. Savetovanju CIRED Srbija, Kopaonik, 12-16. septembra 2022.

UDC: 621.315.685:537.612
621.317.42:614.875

Maja Grbić[1], Dejan Hrvić[1], Aleksandar Pavlović[1]

Analysis of Exposure of People to Magnetic Flux Density in the Apartment Due to the Influence of Low Voltage Cable Terminal Boxes

[1] Nikola Tesla Institute of Electrical Engineering, University of Belgrade, Belgrade, Republic of Serbia *

Category of article: Professional paper

Highlights

- Cable terminal boxes can be a significant magnetic field source when located in close proximity to areas of increased sensitivity
- It is necessary to carry out the first non-ionizing radiation testing in the areas of increased sensitivity with cable terminal boxes on their walls
- Cable terminal boxes can be the non-ionizing radiation source of special interest

Abstract

The paper analyzes the levels of magnetic flux density in the apartment that occur due to the influence of cable terminal boxes. The analysis is based on the results of magnetic flux density measurements in the apartment. In the considered example, the cable terminal boxes are located on the outer wall of the apartment, which leads to increased levels of magnetic flux density in the room located on the other side of the wall. It has been shown that the values of magnetic flux density in the apartment can exceed the value of 4 µT, which is a criterion for the source to be categorized as a source of special interest, in accordance with the provisions of the current national legislation in the field of non-ionizing radiation. The aim of the paper is to show that in the aforementioned configuration the values of magnetic flux density in the apartment can be significant, in order to avoid such technical solutions in the future during the design and construction of new facilities which represent areas of increased sensitivity. The significance of performing testing in apartments and other areas of increased sensitivity with cable terminal boxes in their proximity is also emphasized.

Keywords

Area of increased sensitivity, cable terminal box, magnetic field, magnetic flux density, non-ionizing radiation, reference level

Notes:

The full text of this article is available only in the Serbian language.
In the English version, only its Abstract (given above) is available.

The article (in Serbian) represents an expanded, improved and additionally peer-reviewed version of the paper "*Analysis of Magnetic Flux Density Levels in the Apartment due to the Influence of Low Voltage Cable Terminal Boxes*", awarded by Expert Committee EC-1 *Network Components* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

Received: April 7th, 2023 Reviewed: May 26th, 2023
Modified: June 7th, 2023 Accepted: July 3rd, 2023
*Corresponding author: Maja Grbić, Koste Glavinića 8a Belgrade
E - mail: maja@ieent.org Phone: +381-64-825-97-55

UDC: 621.317.38(497.113)

Milica Porobić[1], Radislav Milankov[2], Dragan Cvetinov[3], Ratko Rogan[4]

Analysis of Delivered Power to the Customer "Barry-Callebaut - Chocolate Factory Novi Sad"

[1] DSO Elektrodistribucija Srbije“ d.o.o. Belgrade, DEPS Control Department, Serbia
[2] DSO Elektrodistribucija Srbije“ d.o.o. Belgrade, ED Zrenjanin Branch, Srbija*
[3] DSO Elektrodistribucija Srbije“ d.o.o. Belgrade, ED Novi Sad Branch, Srbija
[4] DSO Elektrodistribucija Srbije“ d.o.o. Belgrade, NDDC, Srbija

Category of article: Professional paper

Highlights

- Reasons of complaints of end-users of the distribution system
- Measurement of the desired parameters of the quality of electricity
- Analysis of measured values and consideration of the causes of events
- Mutual influences between the end-user and the distribution power system

Abstract

The Distribution System Operator "Elektrodistribucija Srbije" (DSO), when issuing Design and Connection Conditions (DCC) to the users of the distribution system (UDS) under paragraph 4 of those Conditions, clearly defines the basic technical data on the distribution electric power system (DEPS) at the user's connection point. With this data, industrial UDS receives information about the technical characteristics of the settings in DEPS according to which it adjusts its production processes. Otherwise, the production process will be sensitive to the delivery of electricity of technical characteristics defined through DCC.

In the operational management of DEPS, UDS complaints about the quality of delivered electricity occur. Professional services of DSO, after filing a complaint, install an electricity quality analyzer of high technical performance, at the point of connection to UDS. The goal is to obtain a technically high-quality analysis that will determine the causes of the production process stoppage problem at UDS.

This paper aims to present an example from practice in the distribution area "DA Novi Sad" in the area of the branch "Elektrodistribucija Novi Sad", where UDS "Barry-Callebaut-chocolate factory Novi Sad" filed a complaint about the quality of electricity. The results of the monitoring of the delivered electricity are presented in this paper.

Keywords

Power quality, Customer's complaint, Measurement analysis

Notes:

The full text of this article is available only in the Serbian language. In the English version, only its Abstract (given above) is available.

The article (in Serbian) represents an expanded, improved and additionally peer-reviewed version of the paper "*Analysis of Delivered Power to Customer Barry-Callebaut - Chocolate Factory Novi Sad*", awarded by Expert Committee EC-2 *Power Quality in Power Distribution Systems* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

Received: April 6th, 2023 Reviewed: July 3rd, 2023
Modified: July 10th, 2023 Accepted: July 28th, 2023
*Corresponding author: Radislav Milankov
E - mail: Radislav.Milankov@ods.rs

EDITORIAL POLICY AND TOPICS OF THE JOURNAL

When re-starting publishing the Journal “Elektroprivreda”, it has been decided for it to be of scientific and professional nature and to be prepared and published in a new, broader concept and in two languages, in Serbian and English. However, only those manuscripts for which authors from Serbia and region wish so and which are evaluated by reviewers and Editorial Board to have adequate contribution and might be of interest for readers beyond the Serbian speaking area, will be published in English. The Journal is, naturally, open for manuscripts by foreign authors which originals are in English. With the consent of these authors, the approved manuscripts will be translated and published in Serbian, too. Both Cyrillic and Latin versions of published articles are available in Serbian.

The Journal is, typically, published twice a year, and only as an e-version (*on line*). The Journal is an Open Access type, where publishing of the accepted manuscripts is free of charge, without any financial charges to the author. On the other hand, there are no financial liabilities for the Publisher towards the authors, either for submitted or published articles.

The contents of the manuscript submitted for publishing in the Journal has to be an original work of author(s) and it should not be published or publicly presented (either published or presented in a meanwhile, before its first publishing in “Elektroprivreda”), anywhere in the world, or in any form. This rule will not be applied to manuscripts submitted for exceptional, special issues of the Journal that are dedicated to already presented, selected papers from partner conferences, and in this case, such manuscript has to be expanded at least by 30% in comparison to the presented conference paper, improved and additionally reviewed as per the procedure for the manuscripts submitted for regular issues of the Journal.

Only manuscripts having at least two positive reviews by respective experts in the discipline the manuscript refers to, or with majority of positive reviews when more reviewers are engaged, will be published in the Journal.

The Journal accepts manuscripts for consideration and publishes papers of scientific and research nature, particularly manuscripts/papers within the scope of:

- new technologies for providing, processing and exploitation of primary energy resources,
- generation, transmission and distribution of electricity,
- storage and conversion of electricity and heating energy,
- rational consumption of electricity and heating energy,
- development of renewable energy sources,
- information and telecommunication systems,
- organization of power system operations,
- environmental protection,
- rehabilitation of power facilities,
- inventions and innovations,
- restructuring and privatization process in an energy sector,
- electricity markets,
- application of EU legal regulations within the scope of energy; and
- other related disciplines.

The Journal is conceived as a platform and tool for presenting experience, constructive expression and confrontation of views, professional discussion of experts from a profession and practice and from scientific and research institutions and innovation centers. Namely, open exchange of their opinions and experience, regarding strategic development and opting for new technologies may contribute to finding adequate and optimal technical and technological, legal and economic, and organizational and business responses to all challenges coming from decarbonization, digitalization and transition of electric power toward sustainable development.

On behalf of the Editorial Board,

Mr. Vladimir Šiljkut, PhD
Editor-in-Chief

CLASSIFICATION (RANKING) OF MANUSCRIPTS

When reviewing manuscripts and completing a Reviwer's Report, reviewers propose and Editorial Board - in case manuscripts are accepted for publication - determine their category (rank). Classification (ranking) of manuscripts will be done as per the *Rulebook for classification and ranking of scientific journals* (Official Gazette of Republic of Serbia, No. 159 as of 30 December 2020) and the table provided herein:

Scientific articles:	
Original scientific and research paper	Paper presenting previously unpublished results of own research done by a scientific method
Review paper	Paper including original, detailed and critical view of a research problem or discipline where the author(s) made some contribution
Short or pre-communication	An original scientific paper in full form, but less extensive or preliminary in nature
Scientific critique, i.e., discussions and reviews	Discussion of some scientific topic based only on scientific arguments and by applying scientific methods
Professional articles:	
Professional paper	Article offering experience useful in promoting professional practice, but which are not necessarily based on a scientific method
Information article	Editorials, comments, and similar
Report	A book report, computer program report, case report, scientific event report, and similar
Expert critique, i.e., discussions and reviews	Discussion of a certain professional topic

First A. Author[1], Second B. Author[2], Third C. Author[3], ...

Instructions for the preparation of article - the title of the article

(NOT MORE THAN FOUR LINES)

[1] Affiliation of the first author - institution, city, country*
[2] Affiliation of the second author - institution, city, country (if differs from 1)
[3] Affiliation of the third author - institution, city, country (if differs from 1, 2)
…

Category of article: (Editor's input)
UDK: (Editor's input)

Highlights

- Key aspects and messages of the work should be presented in a maximum of four short items/bullets
- The sentences of these items must be short, concise, auxiliary verbs can be omitted
- E.g.: The structure and design of work for publication are considered by the instruction

Abstract

The Abstract of the article should contain a concise description of the problem, applied methods and conclusions. It is an essential part of the article and should be clear and concise. The Abstract should be informative, giving an overview of the issues, the procedure and the main conclusions, results and their significance. Do not write in the first person, do not list references and equations, and avoid abbreviations. It should not contain more than 300 words (in Serbian) to 350 (in English, including definite and indefinite articles before nouns).

Keywords

Specify up to six keywords, separated by commas

Received: (Editor's input) Reviewed: (Editor's input)
Modified: (Editor's input) Accepted: (Editor's input)
*Corresponding author: (phone)
E - mail:

1. INTRODUCTION

The *Elektroprivreda* journal publishes categorized articles: original scientific papers, previous announcements, reviews and technical papers in the field of electrical engineering and energy.

All papers are subject to review. The authors are solely responsible for the originality of the paper, the quality and reliability of the results. By submitting the paper, the authors accept all the rules specified in these Instructions.

This document contains paper preparation instructions. Authors are requested to fully comply with these Instructions when preparing their paper to avoid any problems when printing the paper.

The document is a sample for *Microsoft Word* (version 7 and higher) and is also an example of the desired paper formatting. It contains all the necessary information about the paper format, font type and size, as well as the rules explaining the procedures related to equations, units of measurement, figures, tables and other parts of the paper.

The complete paper containing the manuscript, tables, diagrams, drawings, photographs and full names and surnames of authors with affiliations should be submitted by uploading it to the Manuscript Handling Application, available on the Journal's website, https://epijournal.eps.rs/prijava or, alternatively, by sending it to the following e-mail: epijournal.editor@eps.rs.
The paper should not be more than ten pages long (without the list of references and the title, key messages, short content and keywords in English), except in the case of review papers and special editions of the Journal with extended award-winning papers from conferences, in which case the number of pages is not limited, nonetheless it is recommended that it should not be more than 16 pages long.

The original paper should be presented in A4 format (210x297) mm. The text of the paper should be justified. All margins should be set to 2 cm. The text of the paper should be single-spaced. The paper can be written in Serbian or English. (The editorial board decides which paper will be translated into another language, in order to make them available to as many readers as possible.) The font size for individual parts of the text is as in these Instructions. Complete mathematical derivations should be avoided in the paper. The necessary derivation may be given, if necessary, as a whole, in the form of one or more attachments.

This document can be downloaded directly from the following web address https://epijournal.eps.rs and used as the basis to prepare the manuscript, simply by entering parts of the paper text in certain places in this document.

It is recommended that the paper text begins with an introduction where the problem and task of the paper are formulated. An overview and commentary of the used literature from the specified area should be given and the position and contribution of the paper in relation to the specified literature should be indicated.

2. CHAPTER TITLE (for example: TEXT PREPARATION)

For greater clarity, the text of the paper should be divided into chapters and subchapters. Chapters and subchapters should be numbered with Arabic numerals, subchapters with numbers separated by a period. Please separate the titles of chapters and subchapters from the text before and after the title with one blank line. Line breaks in the text title or subtitle should be avoided.

2.1 Subchapter levels

With subchapters, it is not desirable to go lower than the second level, for example 2.1, 3.3, etc.

2.1.1 Third subchapter level. It is allowed only exceptionally, if this contributes to the methodological and general clarity of the paper text and if written, similar to the subchapter titles, in bold lowercase letters, but ending with a period, after which, in continuation of such line and written in normal font, the first sentence of this subchapter begins.

2.2 Positioning of tables and diagrams

Tables, figures and diagrams may, if necessary, be in one or both columns. All figures and tables should be placed in the text close to, but not in front of, the place in the text where they are first mentioned. Figures and tables in the appendices should be marked in the same way as in the text of the paper.

2.3 First page

In the middle of the first page, the paper title is indicated in bold letters, size 16, *Times New Roman* type. Below the title, the full names and surnames of the authors are listed in size 11 letters. The author's affiliations are listed below the names and surnames, in size 10 letters. After specifying the authors' data, the first page lists the key messages of the paper, a summary of the paper and keywords, in size 11 letters.

If the paper is written and approved for publication only in the Serbian language, after the content described in the previous paragraph, the title of the paper, key messages, summary of the paper and key words in English are listed in the final version of the paper for publication.

If the work was written in English and approved for publication, it will be fully translated and published in Serbian, with identical formatting.

If the paper was written in Serbian and approved for publication in both languages, it will be fully translated and published in English, with identical formatting.

In the lower left corner of the first page, the full information needed to contact the first author of the paper should be specified.

All this is easily realized by using the provided first page template by simply entering the anticipated text in places provided under the Instructions.

2.4 Subtitle (for example: Text of the paper)

The text of the paper should simply be entered instead of the text of the Instructions in this format by entering or copying parts of the text that have been done in accordance with these instructions in places provided for this in the Instructions.

2.5 Equations

Equations should be placed in the middle of the text and numbered with Arabic numerals in small (round) brackets along the right margin of the text. Mathematical software (*Microsoft Equation Editor for MS Word* or *MathType*) should be used for equations. E.g:

$$I_F = I_B = -I_C = \frac{-J\sqrt{3}E_A}{Z_1 + Z_2} \quad (1)$$

Equations should be separated from the text before and after the text with a 6pt space. Symbols used in an equation must be defined before they appear in the equation or immediately after the equation. Reference to an equation in the text is made by specifying the equation number in round brackets (1). If the sentence begins with a reference to an equation, then please use "Equation (1) is ...".

2.6 Tables

Tables should be inserted in the text where they are first mentioned or immediately after. They should be marked with Roman numerals, and the number and name of the table should be placed above the table. E.g:

Table I Duration of simulations and memory usage

ISCAS circuit	CPU time [s]	Memory usage [MB]
c17	2	3.9
c432	62	68.7
c880	160	152.6
c1355	283	178.8

2.7 Figures

Figures should be carefully prepared and inserted into the text in the designated place. The figure number and name must be below the image. Figure number should be marked with Arabic numerals. For the sake of better understanding, please avoid excessive information in the figures. All comments related to figures should be in the header. Typescripts should be chosen carefully to ensure clarity. Please attempt to describe the figure axes with words, not just symbols. For example, it is better to specify the ***time t***, rather than just ***t***. Symbols for units of measurement should be placed in parentheses.

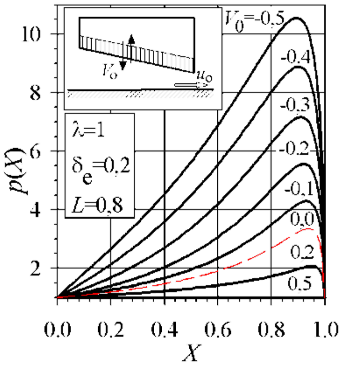


Figure 1. Figure description

3. CONCLUSION

Although the conclusion should contain an overview of the key results of the paper, it should not repeat the part stated in the Summary. The conclusion may explain the importance of the paper or suggest possible applications of the achieved results and provide guidelines for further research on the issues covered by the paper.

ACKNOWLEDGMENTS

Acknowledgments for sponsorship, funding or assistance, if any, should be given as a separate, unnumbered section before the list of references. Please use the singular in the title even when there are several acknowledgements.

REFERENCES

The list of references should be provided at the end of the paper in a separate, unnumbered section. References should be numbered with Arabic numerals in square brackets, according to the order of citation in the text of the paper. When citing, please make sure that the references are accurate and complete, ie. they should fully describe the data sources.

All mentioned references must be directly cited in the text of the paper by stating the reference number in square bracket. Please do not limit yourself to listing your references, but also list relevant references from the field under consideration.

Below are examples of how to cite references: a paper published in a journal [1], a book [2], a chapter in a multi-authored book [3], a paper published in a conference proceedings [4] and an article taken from a website [5].

[1] Šiljak D. D, Stipanović D. M, "Robust stabilization of nonlinear systems - the LMI approach", *Mathematical Problems in Engineering*, Vol. 6, No. 5, pp. 461-493, 2000.

[2] Marković Z., "Granična stanja čeličnih konstrukcija prema evrokodu", Akademska misao, Beograd, 2014.

[3] Deavours D., "UHF RFID antennas", in: Bolić M. (Ed.), *RFID systems - research trends and challenges*, Ch. 3, Wiley, New York, 2010.

[4] Ocokoljić G., Živković S., Subotić S., "Aerodynamic coefficients determinations for the ATM model with

lateral jets simulation - experimental and numerical methods", Proc. *4th International scientific conference on defensive technologies OTEH 2011*, Belgrade, Serbia, pp. 17-22, 6-7 October 2011.
[5] Vukić B., "Društvene igre za visokopozicionirane poslovne ljude" [Internet]. Beograd; Novi Sad: Adizes Southeast Europe; 2010 [citirano 19.03.2012]. Dostupno na: http://www.asee.rs/?page=142&oi=69

APPENDIX (ATTACHMENT) 1

Appendices, if necessary, should be listed after the References. If there are more, they should be numbered with Arabic numerals. In case the attachments contain tables or figures, they should be numbered with the letter "A" followed by a period and a serial number (namely: for tables in Roman, from "I" onwards, in a uniform order for all attachments; and for figures in Arabic, from "1" onwards, uniform for all attachments).

APPENDIX (ATTACHMENT) 2

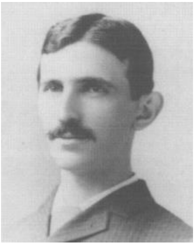
Depending on their content, attachments can be formatted as double-column or single-column. In the case when this allows better visibility for the reader, figures and tables in attachments can be rotated to the left by 90°.

Table A.I Name of the first table of the appendix

Heading	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
Row 1							
Row 2							
Row 3							
Row 4							
Row 5							
Row 6							

BIOGRAPHIES

A short biography should be provided for each author. Please start with the author's first and last name and give his/her short, mostly professional biography. A photo of the author should also be included. A sample biography is provided below.



Nikola Tesla was born in Smiljan in the Austrian Empire on 9 July 1856. He graduated from the Austrian Polytechnic School in Graz and studied at the University of Prague. His work experience included American Telephone Company, Budapest, Edison Machine Works, Westinghouse Electric Company and Nikola Tesla Laboratories. His particular fields of interest were high frequency fields. Tesla received honorary degrees from institutions of higher learning including Columbia University, Yale University, University of Belgrade and University of Zagreb. He received the Elliott Cresson Medal from the Franklin Institute and the Edison Medal from the IEEE. In 1956, the term "tesla" (T) was adopted as the unit of magnetic flux density in the MKS system of units. In 1975, the Power Engineering Society established the Nikola Tesla Award in his honor. Tesla died on 7 January 1943.

Authors shall submit a signed Declaration of Authorship and Originality of the Manuscript to the Editorial Board of the Journal when submitting the paper; the form may be downloaded from the Journal's website, https://epijournal.eps.rs.

Prvi A. Autor[1], Drugi B. Autor[2], Treći C. Autor[3], ...

Uputstvo za pripremu radova - naslov rada
(*NE VIŠE OD ČETIRI REDA*)

[1] Afilijacija prvog autora - institucija, grad, zemlja*
[2] Afilijacija drugog autora - institucija, grad, zemlja (ako se razlikuje od 1)
[3] Afilijacija trećeg autora - institucija, grad, zemlja (ako se razlikuje od 1,2)
…

Kategorija rada: (*unosi Redakcija*)
UDK: (*unosi Redakcija*)

Ključne poruke

- U najviše četiri kratke stavke/*bullets* treba izložiti ključne aspekte i poruke rada
- Rečenice ovih stavki moraju biti kratke, jezgrovite, pomoćni glagoli mogu biti izostavljeni
- Npr: Uputstvom sagledani struktura i oblikovanje rada za publikovanje

Kratak sadržaj

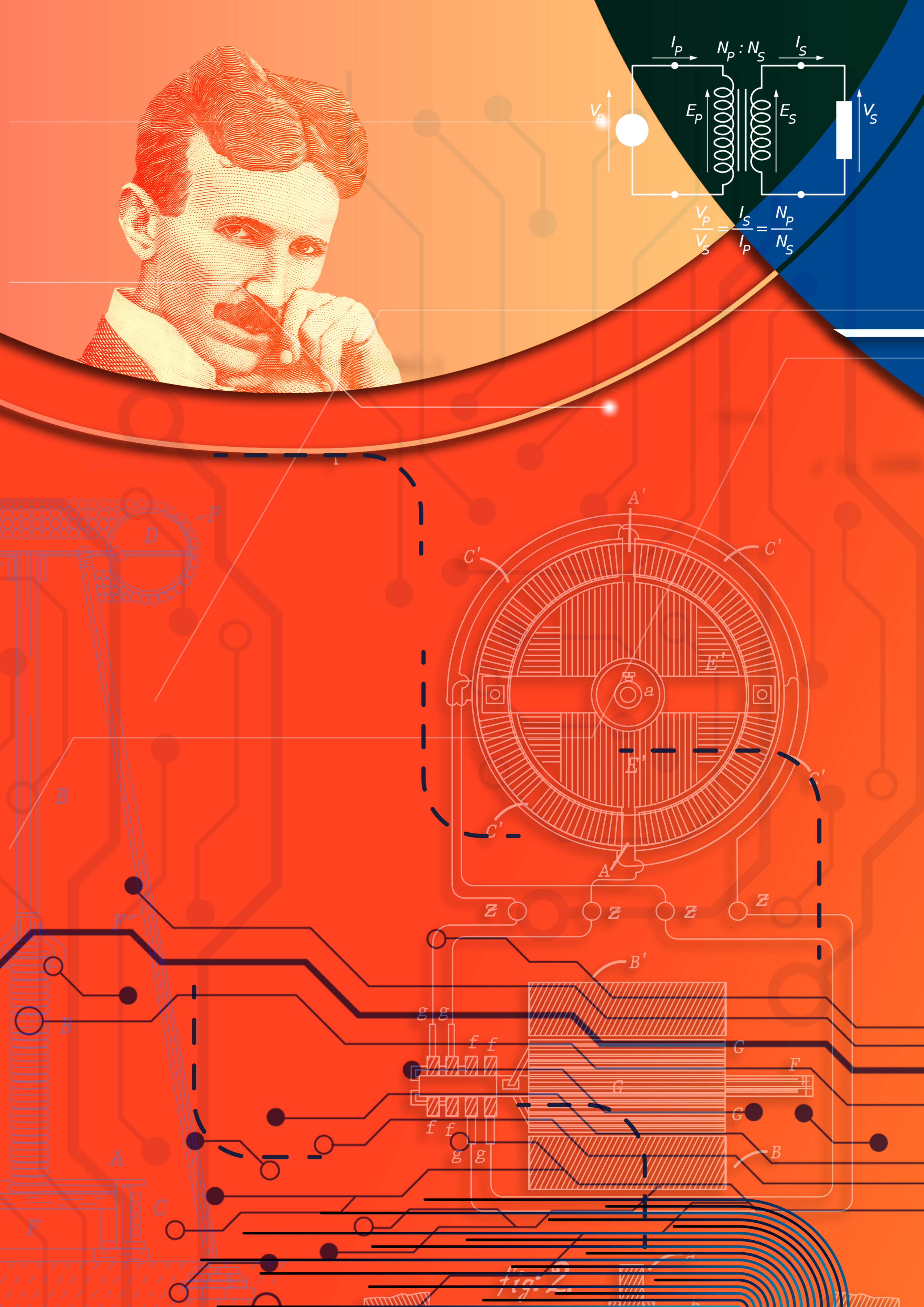
Kratak sadržaj rada treba da sadrži sažet opis problema, primenjene metode i zaključke. On je esencijalni deo rada i treba da bude jasan i koncizan. Kratak sadržaj treba da bude informativan, dajući pregled problematike, postupka i glavnih zaključaka, rezultata i njihovog značaja. Ne treba pisati u prvom licu, ne navoditi reference i jednačine i izbegavati skraćenice. Ne treba da sadrži više od 300 reči (na srpskom) do 350 (na engleskom, uključujući i određene i neodređene članove ispred imenica).

Ključne reči

Navesti do maksimalno šest ključnih reči, odvojenih međusobno zapetama

Primljeno: (unosi Redakcija) Recenzirano: (unosi Redakcija)
Izmenjeno: (unosi Redakcija) Odobreno: (unosi Redakcija)

*Korespondirajući autor: (ime i prezime, telefon)
E - mail:



I_P
N_P : N_S
I_S
V_P
E_P
E_S
V_S
V_P / V_S = I_S / I_P = N_P / N_S
fig. 2