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Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

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CONTENTS

An Approach to Determining Techno-Economic Characteristics of Aggregated Gas Systems

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Abstract — **The unified gas system of the Russian Federation is a complex, multi-line system that encompasses a host of components and connections. It is virtually impossible to create an exact model that adequately describes all its facilities, hence the need for and relevance of the development of methods for aggregating gas systems. The aggregation of such systems can be conventionally divided into two strands: the aggregation of calculated schemes and the aggregation of techno-economic characteristics of their facilities. This study aims to develop methods for determining the aggregated techno-economic characteristics of the gas system facilities. Methodological approaches to aggregating techno-economic characteristics of gas systems and their facilities were analyzed for both Russia and abroad. The procedure of aggregating the calculated gas scheme is given briefly. The study relies on the methods of graph theory, the method of spreading gas costs and losses between source nodes and arcs of aggregated graph; and the method of determining optimal techno-economic indicators for new gas mains and fields (a combinatorial optimization method based on the maximum net present value, given the payback period of new facilities). The proposed approach to aggregating techno-economic characteristics of gas system facilities was employed to create an information base for multi-level modeling of the development of Russia's gas systems and make calculations for the Unified gas system expansion until 2030.**

***Index Terms*: gas system, aggregation, calculated scheme, gas transmission and gas production companies, techno-economic characteristics.**

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I. Introduction

Currently, the gas system (GS) of the Russian Federation includes about thirty natural gas production and transmission companies, most of which are interconnected and constitute the Unified Gas System (UGS). It unites the gas systems of CIS, Eastern and Western Europe, interacts with gas producers in Central Asia and supplies gas to the countries of Northeast Asia. It includes facilities for production (fields), processing (gas processing plants), transmission (line sections of gas mains (GM), compressor stations (CS), gas pumping units (GPU)), underground gas storage facilities (UGS), gas consumers, and others. Solving various problems requires that the characteristics of the facilities be considered to varying degree of detail. This brings about the need for and relevance of the development of methods for aggregating gas systems, in particular, those for determining the aggregated techno-economic characteristics (TEC) of facilities.

The aggregation of gas systems includes the following steps [1]: 1) build an aggregated calculated scheme of a gas system; 2) determine aggregate techno-economic characteristics (TEC) of new and existing gas transmission and gas production companies (GTC and GPC), which also involves demand forecasting for the wholesale natural gas markets; and 3) aggregate in quasi-dynamics by year of the calculation period.

The construction of an aggregated gas system is understood as the transformation of a real-world gas supply scheme into another, simpler one, but corresponding to the original one with certain accuracy, while maintaining the required properties of the original scheme in the resulting one [2].

The aggregated techno-economic indicators of new and existing gas transmission and gas production companies are defined as the calculation of TEC of the facilities for the obtained aggregated gas supply scheme. A special emphasis is made on forecasting the demand in the wholesale natural gas markets.

Aggregation in time refers to studies on the future gas system expansion based on forecast data for certain periods of time.

This paper addresses the issue of determining the aggregated TEC of new and existing facilities of the obtained aggregated calculated scheme of a gas system. The approach to aggregating the calculated schemes is briefly described (section III).

II. Analysis of methodological approaches to aggregation of techno-economic characteristics of gas systems and their facilities

The scale and expansion of energy systems, in particular gas systems, brought about the need to aggregate the calculated schemes and the characteristics of their facilities for further study on the optimal path for their development. The method of constructing the aggregated calculated schemes of gas systems is considered in detail in [3].

Several methods are proposed to determine the techno-economic characteristics [1, 4] and aggregate them for the calculated integrated schemes [1, 5–7]. In [4], the structure, composition and definition of TEC are given with the aggregated characteristics often calculated as averaged values. In [7], the focus is on the iterative aggregation according to which the features of the system and statistical data are studied, and then the main indicators of the system are determined and their weight coefficients are set to calculate aggregated characteristics. The use of this method is limited by the impossibility of collecting a huge amount of detailed initial information on the system. In [5, 6], approaches to the aggregation of indicators from the lower hierarchy level to a higher one are shown; and the method of convolutions of particular values of indicators is used.

Although there is no analogue to the Unified gas system of Russia in the world, researchers in other countries also study the development of large-scale gas systems [8–12]. Papers [13, 14] provide a review and comparison of mathematical models developed in different countries. Foreign models consider networks to varying degrees of aggregation (countries, areas, cities) [15]. Such networks require determining aggregated indicators of capacity, but these calculations are not described. In [14], the lack of transparency in obtaining an aggregated network is said to be a common modeling problem.

The main disadvantages of foreign models are: they use outdated data on the costs of natural gas production and on demand for gas; only long-term costs are taken into account; these models assume that the country has a single gas producer, i.e., aggregated source nodes are characterized by the total cost and capacity, some models consider only the full costs for existing capacities, others factor in the capacity expansion by using coefficients; there is no clear demand analysis; perfect competition in the gas production, transmission, and storage is considered.

An important issue for expansion planning of gas systems is the forecasting of gas demand. Various methods are proposed for long-term forecasting based on changes in the parameters of economic development [16, 17], both at the country level and at the regional level, given local characteristics [18]. At the same time, the socio-economic development of the country can be considered according to two scenarios: innovative and energy export-based [16, 17, 19].

The reliability and accuracy of forecasts are very important. The prevailing opinion is that long-term forecasts should be made in a multivariate way, highlighting not two but three main forecast scenarios, i.e., it is necessary to add an inertial scenario to the innovation and energy export-based scenarios (conservative, target, and basic [20]), or consider optimistic, average, and pessimistic ones with an increase in their divergence as the forecast period is extended [17, 21]. Predictive calculations should observe the balance of quantitative estimates (such as the need and its satisfaction). These studies can rely on both expert assessments and appropriate mathematical models.

The demand for natural gas is normally determined by two methods [14, 22, 23]: a) simplified direct counting method and b) analysis of long-term trends in the gas industry development.

The direct counting method is employed to identify aggregated types of products and services produced by individual sectors of the economy and industry, which consume natural gas. The forecast is based on a study of retrospective data. The indicators of product output and gas consumption rates for the considered period are multiplied, or the dynamics of future demand for natural is determined by multiplying the existing volumes of consumption and the established indices for the estimated periods. The direct counting method is the more reliable the closer the period under consideration.

The method of analyzing long-term trends in the gas industry development is aimed at analyzing the solutions obtained from the model of the national energy sector, the possible quantitative indications of the objective trends that characterize the relationship between the development of the gas industry and that of the country's economy. First, quantitative manifestations of new trends are determined, and then possible hypothesized quantitative manifestations of such trends in the period under review are evaluated.

Some researchers, when determining the demand for gas by country, proceed from information on the area and population of the country, and use specific coefficients of gas consumption per capita [15].

An analysis of the scientific and practical experience available in the world shows that the problem of aggregating gas systems has not been sufficiently studied and systematized. The poorly developed areas of the aggregation of techno-economic indicators of system facilities are:

– the aggregation of several fields into one source node and gas consumers into one consumer node does not factor in the throughput capacity of gas mains between them;

– the coefficients of auxiliary gas consumption and gas leakages are not taken into account for gas production and transmission companies;

– the economic indicators of the system, such as the costs of gas production at source nodes and gas transmission along the arcs of the graph are not considered, which does not allow determining the gas price at the consumer's in the future.

– the gas prices for the consumer in Russia are set according to price zones, which does not always reflect the real costs of gas companies.

The scientific novelty of this study is as follows: the methods have been developed to determine the aggregated techno-economic characteristics of gas sources and gas mains, which are used in building the information base, namely the method of spreading costs and losses between source nodes and arcs of the aggregated graph, and the optimization method based on the maximum net present value (NPV), given the payback period of the facilities.

III. AGGREGATION OF THE CALCULATED GAS SUPPLY SCHEME

Gas system is considered at three levels: 1) gas mains, fields, underground gas storages; 2) gas transmission and gas production companies; 3) Unified gas system of the Russian Federation. When solving the problems of optimal expansion for gas systems, we first address techno-economic characteristics of their components of a lower level (gas mains, fields), then these data are used to determine the characteristics of the GTC and GPC, after which the entire Unified gas system is considered, where the optimal flows, directions and cost of gas transmission are determined.

The gas system is represented as a directed graph and is considered as a set of three subsystems: gas sources, gas main networks, and consumers. The initial data for these systems are:

– ***for the sources***: maximum annual gas production at all fields and for gas production companies in total, operating costs and proportion of gas losses at the GPC. The information used is from the Main Directorate of Natural Resources of the Ministry of Natural Resources of the Russian Federation and the Service of JSC Gazprom;

– ***for the UGS gas mains***: diameters, number of lines, lengths, connection points of all compressor stations, operating costs and the proportion of gas losses at the GTC (auxiliary gas consumption and gas leaks). The UGS maps and collected statistical information used are provided by the JSC Gazprom;

– ***for the consumer***: projections of future demand for gas for constituent entities of the Russian Federation, various industries, and gas exporting countries, which are obtained using the models of the energy sector of the Russian Federation, as well as the data from the General Development Scheme for the gas industry and other sectors of the economy.

Using the developed algorithm [3], shown in Table 1, we obtain an aggregated calculated scheme for the UGS, brought to the level of the constituent entities of the Russian Federation. As a result, each entity is represented by one consumer node and one source node, if the entity has gas fields. The network of gas mains between the nodes is represented by arcs in a single-line representation.

As seen in Table 1, the resulting values for demand for gas (step 2), gas production (step 3), throughput capacity

Table 1. Algorithm for aggregating a detailed gas supply scheme

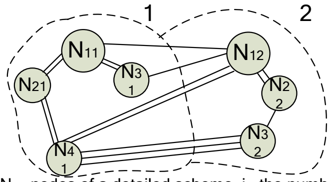
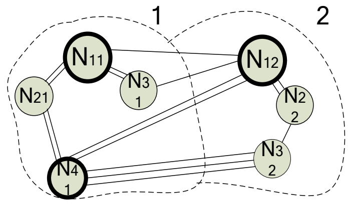
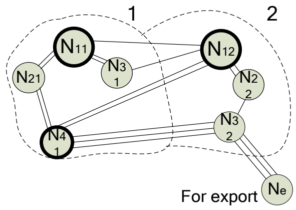
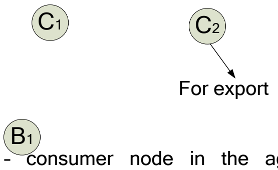
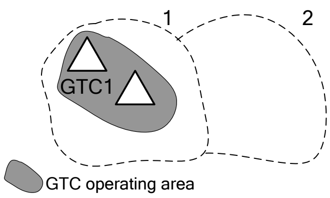
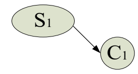
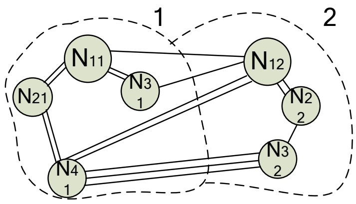
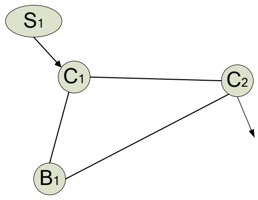
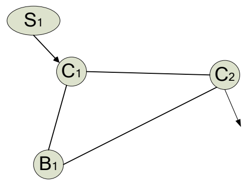
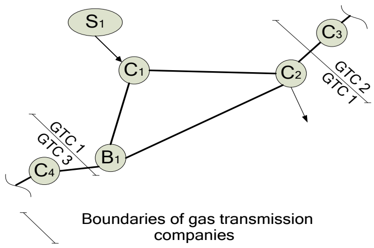
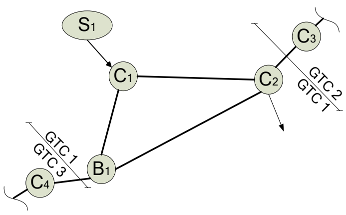
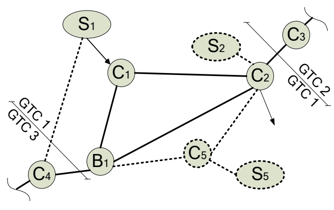
	Actions	Original scheme	Obtained scheme
1. Identify adjacent nodes	1. Identify branching nodes in the scheme.	 N_{ij} - nodes of a detailed scheme, i - the number of node in the entity, j - the number of the entity of RF	
2. Identify aggregated consumer nodes and branching nodes	1. Identify the maximum demand nodes. 2. Match consumer nodes with adjacent branching nodes. 3. Assign the volume of export deliveries from entity to consumer node. 4. Calculate aggregated demand. 5. Select main branching nodes.		 C_i - consumer node in the aggregated scheme B_i - branching node in the aggregated scheme
3. Aggregate source nodes by GPC	1. Identify source node. 2. Determine aggregated production.		 S_i – source node in the aggregated scheme
4. Aggregate gas mains	1. Represent multi-line gas mains by single-line arcs. 2. Determine the throughput capacity of aggregated arcs. 3. Determine the length of arcs.		
5. Glue the obtained aggregated schemes for each GTC into one	1. Connect aggregated schemes along the GTC operating boundaries.		
6. Build a redundant scheme	1. Add projects of new gas pipelines and new fields prepared for the development, and new consumers to the scheme.		

Table 2. Methods for determining the aggregated technical and economic characteristics of the UGS of the Russian Federation

Facilities	Existing gas transmission companies	Existing gas production companies	New gas mains	New fields
Methods	Method of spreading costs and losses		Combinatorial optimization method based on the maximum NPV in terms of the payback period	
Main techno-economic indicators to be determined	1. Costs of gas transmission through pipes of different diameters 2. The cost of gas transmission along the arc 3. Specific costs for transporting 1 000 cubic meters of gas along the arc 4. Coefficients of auxiliary gas consumption and leakage 5. Coefficient of reduction in arc throughput capacity	1. Specific costs of GPC 2. Coefficients of auxiliary gas consumption and leakage 3. Coefficient of reduction in gas production due to losses	1. The number of compressor stations, length of pipes between them 2. Gas pumping units and their sizes 3. Capital investment in and operating costs of gas mains 4. Net present value (NPV) 5. Payback period	1. Production capacity of the field by year 2. Forecast price set 3. Net profit 4. Discount factor 5. Profitability 6. Cash flow 7. NPV 8. Payback period

supply scheme are determined by summing the corresponding values of the detailed scheme, provided they are equal in the original and aggregated schemes.

IV. Modeling of aggregated TEC of gas systems and their facilities

Modeling of aggregated TEC of existing gas transmission companies. Gas transmission companies (GTCs) transport natural gas through the gas pipeline system. Each GTC has its own clear boundaries, provides a certain territory with gas and export gas to other areas. For each existing GTC, the operating costs of the company (the cost of gas transmission), the length of the gas pipeline, the number of lines and diameters, the auxiliary gas consumption (aux) and losses are established based on the standard reference sources.

Table 2 presents the methods for aggregating the main TECs of gas transmission and gas production companies, both existing and new ones.

The prices for gas transportation along the arcs are determined based on the operating costs and the total length of the GTC gas mains, and their diameters. Operating costs, given the coefficients, are spread over the entire total length of gas pipelines. It is known that the operating costs associated with the gas transmission through gas pipelines of large diameters are less than those for the transmission of the same gas volumes through gas pipelines of smaller diameters. Quantitatively, this fact can be determined through the cost overrun factors (y_k) for the transmission of 1 000 m^3 of gas through gas pipelines of various diameters in terms of a gas pipeline with a large pipe diameter taken as a base (normally 1 420 mm), Table 3 [1].

The operating costs of the GTC are given as a table representing the cost estimate.

The need for financial (cash) resources of the GTC given in the table reflects the cost of natural gas transportation for this company. Gas transmission company establishes a rate of return, which stimulates the expanded production of the company and provides personnel bonuses.

The GTC costs can be considered basic costs ($D(B)_{GTC}$) formed at a certain point in time t_B. Basic costs remain unchanged throughout the considered period.

Table 3. Cost overrun factor (γ_k)

Pipeline diameter, mm	Factor, γ_k
1 420	1.0
1 220	1.07
1 020	1.15
820	1.65
720	2.45
529	3.45
Others	4.5

Table 4. Nominal throughput capacities of main gas pipelines of different diameters

Diameters of pipes, mm	1 420	1 220	1 020	820	720	529	426	377	325
Throughput capacity, billion m^3/year	30.0	18.5	9.0	6.2	4.2	2.0	1.0	0.6	0.4

Forecast costs ($D(t)_{GTC}$) at the end of the t-th forecasting step are calculated by the expression [24]:

$$D(t)_{GTC} = D(B)_{GTC} \cdot J(t, t_0),$$

where $J(t, t_0)$ is an index of change in the costs at the end of the t-th step with respect to the initial moment of calculation (t_0).

Transportation rates for 1 000 m^3 of gas along the arcs of the calculated graph (c_{ij}) are determined as follows:

$$c_{ij} = \frac{T_{ij}}{Q_{ij}},$$

where T_{ij} is the cost (forecast costs) of gas transportation by link ij; Q_{ij} is the nominal throughput capacity of link ij, which is found as a sum of throughput capacities of gas main lines aggregated in arc ij.

Cost of transmission along arc ij is calculated as follows:

$$T_{ij} = \sum_{k=1}^{n} \Theta_k L_k,$$

where L_k is the length of gas main with diameter d_k in one-line calculus; Θ_k is price (rate) of gas transmission by the gas pipeline with diameter d_k at a distance of 1 km,

$$\Theta_k = \Theta_k \cdot \gamma_k.$$

Here $k = \overline{1, K}$; K is the number of options for gas pipeline diameters, for example, $d_1 = 1\,420$, $d_2 = 1\,220$, $d_3 = 1\,020$, …

Tariff for gas transmission through the gas pipeline of the first diameter ($d_1 = 1\,420$ mm) is calculated from the expression:

$$\Theta_1 = \frac{D_{GTC}}{\sum_{k=1}^{K} \gamma_k \cdot L_k},$$

where D_{GTC} is the financial requirement of the company, which is taken from the cost estimate table.

Each arc of the aggregated graph displays one or several existing MGs of corresponding diameters. The throughput capacity of this arc (upper limit) is determined as the sum of the nominal throughput capacities of the mentioned gas pipelines. Approximately, their values for MGs of various diameters at a pressure of 7.5 MPa are given in Table 4.

Each edge (arc) of the calculated graph of a gas transmission company displays the lengths of gas mains of corresponding diameters, which are included in this arc. The sum of the gas main lengths for all edges corresponds to the length of the gas pipelines belonging to this company.

Auxiliary gas consumption of main gas pipelines for a year is usually determined based on the number of GPUs in operation, the number of their operating hours per year and their technical characteristics (GPU types, unit capacity, specific fuel consumed by GPUs, efficiency, and others). We propose a simplified method for determining the auxiliary gas consumption, based on the share (percentage) of gas consumed for pumping gas through gas pipelines of gas transmission companies (taken from the reference books of the gas industry for recent years). An analysis of these shares shows a certain stability of their values in dynamics.

The coefficients showing the decrease in yearly gas supply volumes due to the auxiliary gas consumption on the edges of the calculated graph of the gas transmission company are found from the expression:

$$\alpha_{aux_{ij}} = \frac{0.01 \cdot P_{aux}^{GM}}{L} L_{ij},$$

where L is a length of gas pipelines in single-line calculus of the gas transmission company, km; P_{aux}^{GM} *is* the share of gas assumed for calculations, L_{ij} is the lengths of gas pipelines of arc ij on the calculated graph of the gas transmission company, km.

The level of gas losses to the atmosphere at gas industry entities can be divided into background, technologically inevitable, and emergency ones. According to official statistics, in total, these losses range from 3.3% to 7.2% of the annual gas production [1].

The coefficients showing the decrease in yearly gas supply volumes due to gas leakage into the atmosphere on the edges of the calculated graph of the gas transmission company are determined by the following expression:

$$\alpha_{loss_{ij}} = \frac{0.01 \cdot P_{loss}^{GM}}{L} L_{ij},$$

where P_{loss}^{GM} is the gas share of the considered GTC, %.

The coefficient, which simultaneously takes into account the decrease in gas supply volumes per year in a gas transmission company due to auxiliary gas consumption and losses, is as follows:

$$\alpha_{ij} = \alpha_{aux_{ij}} + \alpha_{loss_{ij}} .$$

Modeling of aggregated techno-economic characteristics of the existing gas production companies (GPCs). Based on the reference literature, the state of the raw material base at the fields of the gas-bearing region is determined. The operating costs of a gas production company are given in the form of a table presenting the cost estimate.

The cost estimate is the basic cost of extracting natural gas at a given point in time t_B. The basic costs of a gas production company remain unchanged throughout the entire considered period.

Forecast costs ($D(t)_{GPC}$) at the end of the t-th prediction steps are determined as follows:

$$D(t)_{GPC} = D(B)_{GPC} \cdot J(t, t_0).$$

Here $J(t, t_0)$ is an index of change in the costs at the end of the t-th step with respect to the initial instant of calculation (t_0) (similarly to GTC).

Costs reflect the gas production cost and the profit required for expanded production. Self-financing price (C_{GPC}) is calculated as follows

$$C_{GPC} = \frac{D_{GPC}}{Q_{GPC}},$$

where D_{GPC} is the need of the GPC for financial resources according to cost estimate; Q_{GPC} is the forecast "upper" volume of gas production by the GPC.

The coefficient that factors in auxiliary gas consumption is found from the expression

$$\alpha_{aux}^{GPC} = \frac{P_{aux}^{GPC}}{100}.$$

Here P_{aux}^{GPC} is the share of auxiliary gas consumption of GPC, %.

The coefficient showing the decrease in gas supply volumes per year due to emergency gas leakages is determined from the expression:

$$\alpha_{loss}^{GPC} = \frac{P_{loss}^{GPC}}{100}.$$

Here P_{loss}^{GPC} is a share of gas leakages assumed for GPC, %.

Coefficient that simultaneously takes into account the decrease in yearly gas production volumes at the GPC due to the auxiliary gas consumption and losses (Q_{GPC}) is found as follows

$$\alpha_{GPC} = \alpha_{aux}^{GPC} + \alpha_{loss}^{GPC} .$$

Modeling of techno-economic characteristics of new gas transmission companies (GTCs). The development of new gas transmission projects requires an assessment of their economic and social implications, as well as the costs associated with social activities and environmental protection. The costs and efficiency of the project are assessed for the calculation period. The assessment of the project cost-effectiveness involves the coordination of multi-temporal indicators by reducing (discounting) them to the values in the initial period. The reduction of the costs, results and effects at different times is based on the discount rate (E), which is equal to the rate of return on capital acceptable to the investor.

Comparison of various projects and selection of the best one is based on the following indicators.

1. *Net present value (NPV)*. It is determined as the sum of current effects for the entire calculation period, which is reduced to the initial step, or as an excess of integral results over integral costs [24].

$$NPV = \sum_{t=0}^{T} \left(R_t - З_t \right) \frac{1}{\left(1+E\right)^t},$$

R_t is results achieved at the t-th step of calculation; $З_t$ is costs incurred at the same step; T is calculation horizon.

If the NPV of the project is positive, the project is efficient (at a given discount rate). The higher the NPV, the more economically efficient the project is.

2. *Profitability index (PI)*. PI is the ratio of the sum of effects reduced to capital investments (K)

$$PI = \frac{1}{K} \sum_{t=0}^{T} \left(R_t - З_t^* \right) \frac{1}{\left(1+E\right)^t},$$

where $З_t^*$ is the costs at the t-th step provided they exclude capital investment.

If the NPV value is positive, then $PI > 1$ and vice versa. Thus, if $PI > 1$, the project is economically viable.

3. *Internal rate of return (IRR)*. IRR is a discount rate (E_{aux}), at which the value of the reduced effects is equal to the reduced capital investment, and can be obtained by solving the equation:

$$\sum_{t=0}^{T} \frac{R_t - З_t^*}{\left(1+E_{IRR}\right)^t} = \sum_{t=0}^{T} \frac{K}{\left(1+E_{IRR}\right)^t}.$$

The obtained value of IRR is compared with the rate of return set by the investor. If the value of IRR is greater than the rate of return set by the investor, investment in this project will be justified.

4. *Payback period.* This is the minimum time interval (from the beginning of the project), beyond which the integral effect becomes non-negative.

A simplified algorithm for creating and developing a new gas transmission system and determining its techno-economic characteristics, as well as the wholesale gas sales price, is as follows.

Gas main is considered as a separate newly commissioned facility of the gas system, without connection with the gas source and consumers, and may contain one or more pipes and compressor stations with the same type of gas pumping units. Hydraulic calculations for placing compressor stations and calculations for choosing the number of standby operating GPUs are carried out for normal (standard) gas transmission conditions [1]. The possibility of redundancy due to the storage capacity of the end sections of the main pipelines and due to the forced operation of the gas compressor units within the technical limits is not taken into account.

The calculated scheme of a multi-line gas main is a chain of series-connected links, i.e., sections of pipelines and compressor stations, for which, capital investments and annual costs are determined depending on different combinations of equipment.

The horizon for considering the flow of funds into the gas transmission system is the service life of this system, as a rule, it is 30–35 years, while the payback period is about 7 years.

The gas transmission system is considered as a system of pipelines without gas takeoffs from the pipeline on the route with set annual production capacity Q_G and gas pipeline length L. A list of possible diameters of pipes to be used for the construction of the main gas pipeline, the number of lines and a list of standard sizes of gas pumping units to be installed at the compressor stations are also set.

Specific capital costs for the linear part of the gas main (k_{Li}) covering the costs of the territory preparation, steel pipes and their transportation, auxiliary equipment, construction and installation works, are chosen as the average of the values of specific capital costs for flat-hilly, flooded, permafrost soil and mountain areas with high seismicity (magnitude of earthquakes up to 8). Specific annual investments in the construction of industrial and auxiliary facilities (k_{aux}) include the costs of gas measuring stations, houses of linemen, control stations, landing sites, power supply, electrochemical protection, roads, communications, and remote control. Specific annual investments in housing and social facilities consist of the costs of housing construction, given the housing cost ($k_{h.c.}$). The total specific annual investments in the linear part of the gas pipeline depending on diameter are equal to the sum of the above values:

$$K_{link\ i} = k_{Li} + k_{aux} + k_{h.c.}.$$

Specific annual operating costs of the linear part represent the costs of labor, allocations for social needs, depreciation, and other costs (S_{Li}).

Specific annual investments in compressor stations equipped with various types of gas pumping units include the cost of preparatory work, compressor shop, gas treatment, purification and cooling units, technological networks, auxiliary facilities, off-site facilities, gas pipelines, and flow lines ($k_{cs\ j}$).

Specific annual operating costs for the compressor station, which depend on the installed capacity and type of GPU, include tangible costs, costs of gas for auxiliaries, labor costs, allocations for social needs, depreciation, and other costs (S_j).

Specific annual operating costs for the compressor station, which do not depend on the installed capacity, are determined by the share of the annual costs for the compressor station, as per the size of gas pumping units ($S_{n\ j}$).

The net present value of the gas pipeline designed and the payback period are determined by the cash flow algorithm (simplified business plan) [25]:

Consider various options of standard sizes of GPU and pipes. Select the calculation in which the NPV has the highest value. Compare the payback period of the project of this option with the payback period norm. If the payback period is less than or equal to the norm, then the calculation is completed. If the payback period is longer than the norm, then the accepted gas sale price is increased by some given value. The process of iterative calculations ends if the payback period is less than or equal to the norm of the payback period.

Modeling of techno-economic characteristics of new gas production companies (GPCs). In the context of insufficient information on newly discovered fields, we propose the following simplified algorithm for determining the aggregated techno-economic characteristics of the GPC.

1. Find similar existing projects based on exploration data and a preliminary geological assessment of the field. By analogy with these projects, estimate gas production

Table 5. Gas consumption by constituent entities of the Russian Federation and gas export to FSU and non-FSU countries, billion m^3

		2020			2025			2030		
No	Node	Internal	Export	Total	Internal	Export	Total	Internal	Export	Total
1	Belgorod	8.6	0	8.6	11.2	0	11.2	14.5	0	14.5
2	Bryansk	3.6	0	3.6	4.1	0	4.1	4.7	0	4.7
3	Gavrilov–Yam	18.8	0	18.8	20.5	0	20.5	22.4	0	22.4
4	Novopskov	8.8	11	19.8	12.4	9	21.4	17.5	7	24.5
5	Kaluga	3.1	0	3.1	4.2	0	4.2	5.7	0	5.7
6	Kursk	3.3	40	43.3	3.6	25	28.6	3.9	25	28.9
7	Dace	6.4	0	6.4	6.4	0	6.4	6.4	0	6.4
8	Moscow	50.0	0	50.0	52.3	0	52.3	54.7	0	54.7
…	…	…	…	…	…	…	…	…	…	…

Table 6. Calculated techno-economic indicators of gas transmission links for the aggregated gas supply scheme

			2020		2025		2030	
Arc	α	Q max	Q, bn.m^3	C, USD/1000 m^3	Q, bn.m^3	C, USD/1000 m^3	Q, bn.m^3	C, USD/1000 m^3
Kursk–Belgorod	0.999	13.2	8.61	1.1	11.21	1.2	13.20	1.3
Kursk–Orel	0.999	13.0	6.41	2.0	7.11	2.2	8.01	2.3
Yelets–Tula	0.997	54.0	9.53	1.2	9.93	1.3	10.43	1.5
Yelets–Kursk	0.998	130.0	58.44	0.3	47.02	0.3	50.21	0.4
Yelets–Novopskov	0.998	48.2	48.20	2.2	48.20	2.5	48.20	2.6
…	…	…	…	…	…	…	…	…

(Q), capital investments (K), fixed assets (FA) and costs, given that costs rise every year due to inflation.

2. Build a schedule of production by year, depending on the maximum possible annual demand for gas of the field. Production goes up for the first three to five years, then the maximum capacity (approximately 10 years) is used, then production declines. Determine production capacity by year (Q_t).
3. Calculate the forecast price (P_t) of gas at the end of the t-th year of calculation by the formula [24]: $P_t = C_0 \cdot J_t$, where J_t is the index of changes in the prices of products or resources of the corresponding group at the end of the t-th step with respect to the initial instant of calculation (at which prices are known). Set the value of J_t according to the projections of the Russian economy.
4. Determine revenue for each year: $R_t = Q_t \cdot P_t$; costs (C_t) are set in % of FA; gas prime cost: $S_t = C_t / Q_t$; balance sheet profit: $BP_t = R_t – C_t$; income tax $IT_t = n$; BP_t (n is the rate of tax on taxable profit); net profit $NP_t = BP_t – IT_t$; discount factor: $a_t=1/(1+E_t)^t$ (E_t is the discount rate); attracted investments $AI_t = I_t – S_d t – NP_t$, if $AI_t < 0$, then the attracted investments are assumed to be equal to 0; product profitability: $P_t = (R_t – C_t)/C_t$.
   Investments over the periods can be characterized by both revenues and costs. If for the period under review, revenue exceeds costs, this means the net revenue or positive cash flows; if costs exceed revenues, then there are net costs or cash outflows. Some cash flows are subject to taxation, they should be calculated after the tax assessment.
5. Determine cash flow ($CF_t = NP_t + C_{d\,t} – I_t$) and net present value ($NPV_t = CF_t{\cdot}a_t$).
6. Calculate loan payments if $CF_t > 0$.
7. Define the payback period as the time required for the revenues from an investment project to become equal to the initial investment in this project. If the cash flow from the investment project is expected to be constant over several years, the payback period can be found by dividing the initial investment by the expected annual revenues. If the expected flow of earnings varies from year to year, then the payback period can be determined by summing the expected revenues over the years until

Table 7. Addition of new capacities in the gas transmission system by year

Initial node	Final node	Capacity, billion m^3		
		2020	2025	2030
Novopskov	Rostov-on-Don	30		
Syktyvkar	Gryazovets	50		
Gryazovets	St. Petersburg	30		
Gryazovets	Torzhok	30		
Rostov-on-Don	Maykop	30	60	
Ukhta	Pomary	60		120
Yamal	Ukhta		140	90
…	…	…	…	…

their total equals the initial investment. To determine the payback period, the number of periods (years) in which $NPV < 0$ is calculated.

8. Compare the payback period of the project with its norm equal to 7 years. Complete calculations if the payback period becomes less than or equal to this norm. Otherwise, set a higher value of the price P_t, and repeat the calculation until this condition is met.

V. Results of research on the UGS expansion until 2030 based on the proposed approach

Based on the approach proposed, a redundant aggregated scheme was built and an information base of techno-economic indices of unified gas system facilities was created. The calculated indicators for the aggregated scheme, for example, gas consumption at consumer nodes, arc capacities and loss factors are given in Tables 5 and 6 (columns 2, 3), respectively.

The possibilities for the development of gas systems in Russia, given the internal needs of the markets and specified export deliveries to the FSU and non-FSU countries were assessed using a network flow model. The quasi-dynamics of the gas system development in European Russia together with eastern part of the gas industry was calculated for 2025 and 2030.

The calculation results for existing and new gas transmission systems of the aggregated scheme are shown in Table 6. Their analysis suggests the need for the construction of new gas pipelines, which are presented in Table 7.

Table 8 presents the results of gas flow calculations for the aggregated Unified gas system for 2025 and 2030, corresponding to the average scenario of economic development.

Table 8. Balance of the main indicators of the gas industry development, billion m^3

Item	Years	
	2025	2030
Gas consumption in Russia, total:	507 – 593	517 – 641
Entity 1	120 – 140	120 – 146
Entity 2	124 – 150	129 – 170
…	…	…
Export, total:	270 – 395	285 – 430
Non-FSU countries	230 – 320	230 – 350
FSU countries	40 – 75	55 – 80
Gas consumption for process needs of gas mains	58 – 73	58 – 75
Total gas for distribution	835 – 1061	860 – 1146
Gas production in Russia, total	799 – 1049	827 – 1068
Source 1	450 – 490	350 – 450
Source 2	230 – 300	330 – 420
…	…	…
Gas supply from Central Asia	35 – 40	30 – 40
Gas resources, total	835 – 1061	860 – 1146

VI. Conclusion

1. The paper has briefly presented an approach to aggregating a real-world gas system, i.e., presenting it in the form of a simpler calculated scheme characterized by a smaller number of nodes and connections.
The proposed approach makes it possible to take into account small fields, independent gas producers, and minor gas mains both between the entities and within them.

2. Methods for aggregating the techno-economic characteristics of both existing and new gas system facilities have been developed: the method of spreading costs and losses between the arcs and source nodes of the aggregated graph is used for existing GTCs and GPCs; a combinatorial optimization method based on the maximum NPV, given the payback period of the facilities is employed for new GTCs and GPCs.

The proposed procedure for aggregating techno-economic indices makes it possible to factor in the capacity of small gas mains between several source nodes or consumers of a detailed scheme, and coefficients of auxiliary gas consumption and leakage for GPCs and GTCs.

3. The proposed approach has been applied to aggregate Russia's gas system scheme, create an information base for multi-level modeling of the gas system development in Russia until 2030, analyze the current state of the gas industry of the Russian Federation (gas production, gas transmission, and demand for gas in various industries); determine the techno-economic characteristics of its facilities; and identify the prospects for the expansion of gas supply to the constituent entities of the Russian Federation.

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A Methodology for Performance and Reliability Analysis of Prosumers' Local Heat Sources in District Heating System

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***Abstract* — The paper focuses on two problems addressed in the studies on the prosumer in district heating systems. The first problem is associated with load distribution in the district heating systems with prosumers. The research proposes a bi-level model for solving this problem to determine an optimal balance between the load of district heat sources and prosumer-owned heat sources. The second problem concerns the reliability of heating for consumers to be provided through the optimal distribution of reliability parameters among components of the system, given the capabilities of the prosumer to supply part of load by their heat sources. The methods and models are proposed to solve this problem. They are based on the theory of random processes, theory of hydraulic circuits, and basic laws of cogeneration. The case study results obtained using the developed methodology demonstrate a potential economic benefit and reliability effect of involving the prosumer in heat supply. The conclusions and directions for further research are formulated.**

***Index Terms*: District heating system, prosumer, mathematical modeling, optimal operating, bi-level programming, reliability ensuring, nodal reliability indices, markov random process.**

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I. INTRODUCTION

The intensive development of energy and information technologies affected greatly the theory of energy system design. The core principles of this theory are the integration of different generators, transition to intelligent systems (i.e., the system's capability to generate and implement solutions based on the forecast and analysis in combination with self-learning), and an increasing involvement of the consumer in energy supply. The latter principle is implemented within the prosumer (producer-consumer) concept. The prosumer functions are regulation and optimization of their demand to enhance the efficiency and reliability of both the prosumer and the entire energy system. Prosumers have their sources and energy storage devices that enable them to vary the amount of power received from the system and its properties (reliability, losses, quality, and others) based on the balance between their needs and capabilities. Researchers in many countries conduct theoretical and practical studies on the prosumer. The investigations to be emphasized are presented in [1–7]. They focus on various aspects of prosumer operation and control within power supply systems. The papers [8] and [9] deal with some issues of prosumer operation in the district heating systems (DHS). Some optimal management options for DHS with prosumers with focus on reliability are considered in [10–12]. Following the analysis of publications on the prosumer topic, which is part of a more general theory of intelligent integrated energy systems (Smart Grid), we can conclude that almost all these investigations concern electric power systems. At the same time, these technologies are also relevant for DHS, which are the largest fuel consumers, especially in Russia, where the fossil fuel consumption for heating needs exceeds 45% of the total values.

One of the main objectives of involving the prosumer (hereinafter, heat prosumer) in the DHS is to enhance the efficiency and cost-effectiveness of the system by managing the optimal distribution of sources supplying heat loads. The methodological problems to be solved to achieve this objective are various and traditional for energy systems and DHS, in particular. The involvement of prosumers in the DHS, however, brings about new aspects in these problems and calls for new methodological approaches to solve them. The development of these methods is a subject of the presented paper.

II. A Bi-Level Model for Management of DHS with Prosumers

The management of DHS with prosumers implies distribution of heat load among system district heat sources (HSs) and local HS that belong to prosumers according to some criteria providing the required (anticipated) parameters of system operation. The inclusion of prosumers with their HSs in the DHS changes the organizational model of the system operation. Thus, the need arises to consider the management at two levels – district heat sources (system level) and the prosumer self-generation (prosumer level).

Mathematically, the problem of managing the DHS with prosumers is solved by the *bi-level programming* methods [13–16]. Such methods are used in different fields of science and technology to solve multi-criteria problems, especially in the case of conflicting interests of the studied subjects. For example, the focus of [16] is on a bi-criterion framework designed to minimize cost and risk together under constraints with the view to determining the optimal error identification and patching time for solving the problem for the software. The management structure of DHS with the prosumer is based on a hierarchical bi-level approach and is as follows. At the first level, we solve the problem of cost minimization for the prosumer. The objective function represents a sum of heat purchase costs and heat production costs for the prosumer-owned HSs. The second level of management corresponds to the system for which the problem of profit maximization is posed. The profit is defined as revenue from selling the heat produced by district heat source less its production costs.

The DHS and prosumer interact as follows: 1) the prosumer submits a bid for the amount of heat they need; 2) the system submits a price offer obtained according to its profit maximization; 3) the prosumer chooses optimal load distribution for load supply from the system (from the district HS) and from prosumer's HS according to the cost minimization to be achieved and makes a bid for the load again. In this cycle, an equilibrium that satisfies both participants of the interaction is determined. The bi-level optimization model of managing the DHS with the prosumer is formulated as follows:

1) the objective functions are:

$$F_{\text{obj}}^{(1)} = \sum_{j\in J}\sum_{\tau\in T}(c_{j\tau}^{h} q_{j\tau}^{\text{sys}} + \alpha_j q_{j\tau}^2 + \beta_j q_{j\tau} + \gamma_j) \to \min; \quad (1)$$

$$F_{\text{obj}}^{(2)} = \sum_{j\in J}\sum_{\tau\in T} c_{j\tau}^{h} q_{j\tau}^{\text{sys}} - \sum_{i\in I}\sum_{\tau\in T}(\alpha_i q_{i\tau}^2 + \beta_i q_{i\tau} + \gamma_i) \to \max; \quad (2)$$

2) the load curve of the consumer is:

$$q_{\text{o}j\tau} = q_{\text{o}j}[1-(1-\omega_j)(\tau/\tau_{\text{o}})^{\sigma_j}],\ j\in J,\ \tau\in T; \quad (3)$$

3) the flow distribution model is:

$$\mathbf{A}\mathbf{x}_\tau = \mathbf{g}_\tau,\ \tau\in T; \quad (4)$$

$$\overline{\mathbf{A}}^{\text{T}}\mathbf{p}_\tau = \mathbf{h}_\tau - \mathbf{H}_\tau,\ \tau\in T; \quad (5)$$

$$\mathbf{S}\mathbf{X}_\tau\mathbf{x}_\tau = \mathbf{h}_\tau,\ \tau\in T; \quad (6)$$

4) energy flow balances are:

$$\sum_{i\in I} q_{i\tau} - \sum_{j\in J} q_{\text{o}j\tau} = 0,\ \tau\in T; \quad (7)$$

$$q_{\text{o}j\tau} = q_{j\tau}^{\text{sys}} + q_{j\tau},\ j\in J,\ \tau\in T; \quad (8)$$

5) constraints on variables and parameters are:

$$q_{\text{o}j\tau} > 0,\ q_{j\tau}^{\text{sys}} \ge 0,\ c_{j\tau}^{h} > 0,\ j\in J,\ \tau\in T; \quad (9)$$

$$0 \le q_{j\tau} \le q_{j\max},\ j\in J,\ \tau\in T; \quad (10)$$

$$q_{i\min} \le q_{i\tau} \le q_{i\max},\ i\in I,\ \tau\in T; \quad (11)$$

$$p_{j\min} \le p_{j\tau} \le p_{j\max},\ j\in J,\ \tau\in T. \quad (12)$$

Here: j is a heat consumer; J is a set of heat consumers (including prosumers); i is a district heat source; I is a set of district heat sources; τ is time instant corresponding to the number of hours with a specified load of consumers, h; T is a set of time instants corresponding to the number of hours with a specified load; $F_{\text{obj}}^{(1)}$ is objective function of the first level (consumer), EUR; $F_{\text{obj}}^{(2)}$ is objective function of the second level (system), EUR; $c_{j\tau}^{h}$ is heat price for consumer j at time instant τ, EUR/GJ; $q_{j\tau}^{\text{sys}}$ is part of heat load of consumer j, which is supplied from the system (by district HS) at time instant τ, GJ/h (only for prosumer); $q_{j\tau}$ is part of heat load of consumer j, which is supplied by their heat sources (only for prosumer) at time instant τ, GJ/h; α_j

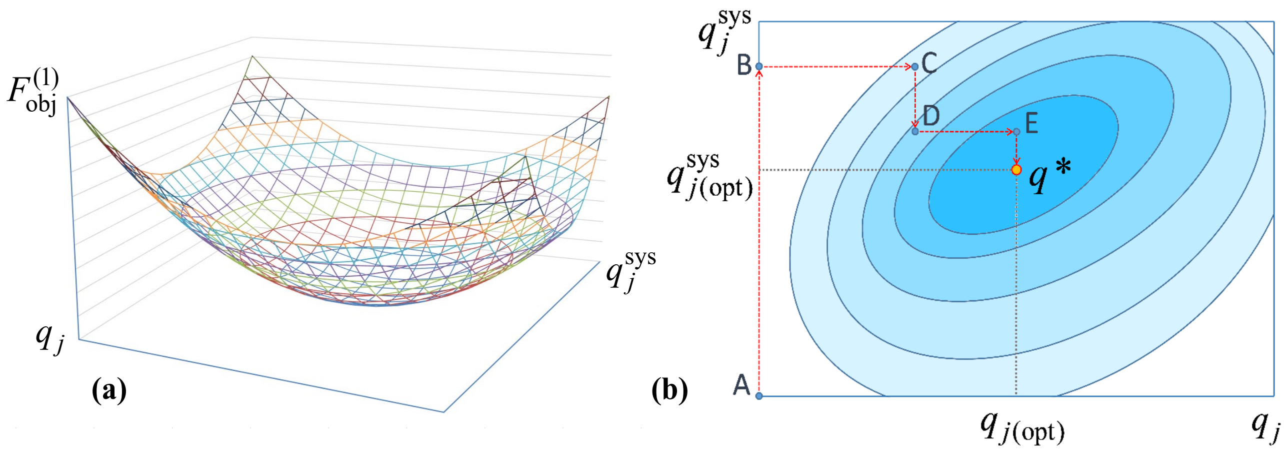

Fig. 1. Graphical illustration of a computational process of search for an optimal solution to the problem of managing DHS with the prosumer: (a) the objective function form is in a three-dimensional system of coordinates; (b) a projection of the objective function plot to the plane of coordinates of heat loads of sources and the solution search procedure.

and α_i, β_j and β_i, γ_j and γ_i are coefficients of cost function for consumer j and the i-th district HS respectively; $q_{i\tau}$ is performance of the i-th district heat source at time instant τ, GJ/h; q_{oj}, $q_{oj\tau}$ are design (maximum) heat load and the heat load of consumer j, which corresponds to time instant τ, GJ/h; ω_j, σ_j are heat load irregularity factors for consumer j; $\mathbf{A}$ is incidence matrix of linearly independent nodes of the heat network (HN); $\overline{\mathbf{A}}^{\mathrm{T}}$ is complete transpose of node-branch incidence matrix for HN; $\mathbf{x}_\tau$ is vector of heat carrier flow rates in the HN branches at time instant τ, t/h; $\mathbf{g}_\tau$ is vector of flow rates at network nodes at time instant τ, t/h; $\mathbf{p}_\tau$ is vector of HN nodal pressure at time instant τ, Pa; $\mathbf{h}_\tau$ is vector of head losses in the network branches at time instant τ, Pa; $\mathbf{H}_\tau$ is vector of operating heads at the sources at time instant τ, Pa; $\mathbf{S}$, $\mathbf{X}_\tau$ are diagonal matrices of coefficients of hydraulic resistances of branches, m/(h^{2}t^2), and absolute values of flow rates in them, t/h, at time instant τ respectively; $q_{i\min}$, $q_{i\max}$ are minimum and maximum values of the i-th district HS capacity, GJ/h; $q_{j\max}$ is maximum value of the HS capacity for consumer j (for prosumer), GJ/h; $p_{j\min}$, $p_{j\max}$ are minimum and maximum values of the heat carrier pressure at nodes of consumer j, Pa. Expression (3) is used to specify a consumer load at each instant of the considered period (a heating season) based on the Rossander equation from [17]. Expressions (4) – (6) represent a model of flow distribution in heat network written in a matrix-node form, which is traditional for the *Theory of hydraulic circuits* (THC) [18]. Parts of expressions in (1) and (2) that define heat production costs at HS are presented as quadratic dependences derived by approximating the real-life data.

With the methods presented in [19–21], the considered problem (1) – (12) can be transformed as follows:
Find:

$$F^{(1)}_{\mathrm{obj}\tau} = c^h_{i\tau} q_{i\tau} + \sum_{j\in J_i} (\alpha_j q^2_{j\tau} + \beta_j q_{j\tau} + \gamma_j) \to \min; \qquad (13)$$

subject to:

$$q_{i\tau} = (c^h_{i\tau} - \beta_i)/2\alpha_i,\ i \in I,\ \tau \in T; \qquad (14)$$

under conditions and constraints (3)–(12).

Here: $F^{(1)}_{\mathrm{obj}\tau}$ is an objective function of the first level determined at time instant τ, EUR/h; $c^h_{i\tau}$ is the price of heat generated at the i-th district HS at time instant τ, EUR/GJ. Thus, after the transformations, the management problem of DHS with the prosumer (13) – (14) with (3) – (12) represents, unlike the initial form (1) – (12), a traditional mathematical programming problem. Figure 1 demonstrates a graphical illustration of the computational process of search for an optimal solution to the management problem of DHS with the prosumer.

The spatial view of the objective function is presented in Fig. 1a and its projection on the system of coordinates of heat loads of the sources – in Fig. 1b. Elliptic lines in this diagram are isocost lines, i.e., the lines of equal costs. The dotted line A-B-C-D-E-q^* corresponds to a step-by-step procedure of search for a solution. The formulated problem is solved by the coordinate descent method with a simple iteration within the cycle to reduce the multidimensional optimization problem to a one-dimensional one with a step-by-step procedure for improvement in solutions according to the heat production output by all the sources.

III. Methods and Models to Ensure the Reliability of DHS with Prosumers

3.1. Statement of the problem

The development of methods for reliability analysis and optimization of the DHS with the prosumer generates two main lines of investigations. The first line is related to analysis and optimization of heat supply reliability, considering the prosumer functions in the system, provided the quantity, nodes and capacity of the prosumer sources are specified. The second line represents the problem aimed at determining the number of prosumers, their connection points, and capacities.

This paper focuses on the first reliability problem, which implies the determination of the values of reliability parameters (failure and restoration rates) for the DHS components, which ensure the required reliability level of heat supply to consumers, including prosumers (given their additional redundancy), at a minimum cost of reaching these values within their feasible range. Two main *reliability indices* are assumed to assess the level of heat supply reliability from [22]. These are *failure free operation probability R_j* (FOP) and *availability factor K_j* (AF).

The indices are determined for each consumer $j \in J$, where J is a set of consumers in the system (including prosumers). The standard values of these indices are denoted by R_{oj} and K_{oj}.

The stated problem is solved for these reliability indices according to a technique consisting of 4 stages:

1) determine relationships between the average reliability parameters of DHS components;
2) model the DHS post-emergency conditions;
3) model the prosumer functions;
4) formalize the problem of determining optimal reliability parameters of the DHS components.

3.2. The relationship between the average reliability parameters of DHS components

The average reliability parameter of DHS components is taken to mean their failure or restoration rate that preliminarily has the same value for these components, which provides the required level of reliability indices. These parameters are determined based on expressions for calculation of nodal reliability indices [22], Rossander equation that determines annual heat load curves of consumers from [17], and some basic laws of district heating and thermal physical processes that occur in the system [23]. Based on these expressions, we determine the following relationship between the average reliability parameters of DHS components, given the fulfillment of FOP and AF conditions:

$$\overline{\lambda}_j = \frac{1}{\tau_o}\left(\ln\frac{1}{R_{oj}}\right) \times \left(1 - N_s(1-K_{oj}) \Big/ \sum_{s\in E} L_s^{1/\sigma_j}\right)^{-1} \times \left(\sum_{s\in E} M_s^{1/\sigma_j}\right)^{-1}; \quad (15)$$

where

$$L_s = \frac{1}{1-\omega_j}\left[1 - \frac{1}{q_{oj}}\left(q_{sj} + \varphi_j\left(t_{sj} - \frac{C_1 - C_2\exp B_j}{C_3(1-\exp B_j)}\right)\right)\right]; \quad (16)$$

$$M_s = \frac{1}{1-\omega_j}\left(1 - \overline{q}_{sj} + \frac{\varphi_j t_{sj}}{q_{oj}} - \varphi_j\frac{C_1 - C_2\exp B_j}{C_3 q_{oj}(1-\exp B_j)}\right); \quad (17)$$

$$C_1 = t_{oj}(1-\overline{q}_{sj}),\ C_2 = t_{j\min} - t_{oj}\overline{q}_{sj},\ C_3 = 1-\overline{q}_{sj}; \quad (18)$$

$$\overline{q}_{sj} = q_{oj}/q_{sj},\ s\in E,\ j\in J; \quad (19)$$

$$B_j = 1/(\varepsilon_j\overline{\mu}_j),\ j\in J. \quad (20)$$

Here: $\overline{\lambda}_j$ and $\overline{\mu}_j$ are average failure and restoration rates for consumer j respectively, 1/h; τ_o is time instant corresponding to a total number of hours of the considered period (heating season), h; N_s is the quantity of system states; s is number of system state; E is a set of system states; ω_j, σ_j are irregularity factors of heat load curve of consumer j [17]; q_{oj} is design (maximum) heat load of consumer j, GJ/h; q_{sj} is level of heat supply to consumer j in system state s, GJ/h; φ_j is coefficient of specific heat losses for consumer j, GJ/(h°C); t_{sj} is current internal temperature for consumer j in state s, °C; $\overline{q}_{sj}$ is relative heat supply to consumer j in system state s, GJ/h; t_{oj} is design temperature of internal air for consumer j, °C; $t_{j\min}$ is minimum admissible temperature of internal air for consumer j, °C; ε_j is coefficient of thermal energy storage for consumer j, h; L_s, M_s, C_1, C_2, C_3, B_j are assumed abbreviations of expressions.

3.3. Modeling the prosumer functions

The prosumer functions in the emergency conditions, which limit or totally terminate heat supply, are to eliminate heat undersupply by their source and increase time redundancy. These properties of the prosumer are considered in the calculation of indices $\overline{q}_{sj}$ and B_j. The following expressions are added to equations (19) and (20):

$$\overline{q}_{sj} = q_{oj}/(q_{sj}^{\text{sys}} + q'_{sj}),\ s\in E,\ j\in J; \quad (21)$$

$$B_j = 1/[(\varepsilon_j + \Delta\varepsilon_j)\overline{\mu}_j],\ j\in J. \quad (22)$$

Here: q_{sj}^{sys} is part of heat load of consumer j, supplied from the system (by district HS) in system state s, GJ/h; q'_{sj} is capacity of HS for consumer j (prosumer) in system state s, GJ/h; $\Delta\varepsilon_j$ is additional passive time reserve of prosumer (caused by the use of their heat generators and/or heat storage devices), h. It is worth noting that time reserve (both active and passive) is one of the most effective methods to improve the reliability of functioning of various technical systems. Therefore, for example, in the study [24], based on the theory of semi-markov processes with a common phase space of states, a semi-markov model of a multicomponent system with a group instantly replenished time reserve is constructed. The index q'_{sj} can be fixed and correspond to a rated (required) value of capacity of the prosumer HS. This index can vary and factor in the component failures decreasing the heat source performance. Here, corresponding failures should be added to a set of system states. In this case, the solution should be based on an analysis of the initial characteristics of equipment reliability. If the failure flow values for the equipment of the prosumer heat source are much lower than those for the DHS equipment, then the failures at the prosumer heat source can be neglected and value q'_{sj} can be assumed to be fixed according to their required performance under specified emergency heat supply to consumers.

3.4. Modeling the post-emergency conditions

Post-emergency hydraulic conditions are determined by flow distribution in the heat network after the disconnection of a failed component. The hydraulic conditions are calculated by the THC methods [18]. The nodal form of the model of flow distribution (hydraulic conditions) in the heat network is represented by a matrix form [18]:

$$\mathbf{A}\mathbf{x}_s = \mathbf{g}_s,\ s \in E; \tag{23}$$

$$\overline{\mathbf{A}}_s^{\mathrm{T}}\mathbf{p}_s = \mathbf{h}_s - \mathbf{H}_s,\ s \in E; \tag{24}$$

$$\mathbf{S}\mathbf{X}_s\mathbf{x}_s = \mathbf{h}_s,\ s \in E. \tag{25}$$

Here: $\mathbf{A}_s$ is incidence matrix of linearly independent nodes in the network under emergency system state s (considering failure of some component); $\overline{\mathbf{A}}_s^{\mathrm{T}}$ is full transposed node-branch incidence matrix; $\mathbf{x}_s$ is vector of heat carrier flow rates in the network sections (branches) under emergency system state s, t/h; $\mathbf{g}_s$ is vector of flow rates at network nodes under emergency system state s, t/h; $\mathbf{p}_s$ is vector of nodal pressures of HN under emergency state s, Pa; $\mathbf{h}_s$ is vector of heat losses in the sections under the emergency system state s, Pa; $\mathbf{H}_s$ is vector of operating heads at sources in the emergency system state s, Pa; $\mathbf{S}, \mathbf{X}_s$ are diagonal matrices of coefficients of hydraulic resistance of sections, m/(h^{2}t^2), which are built from the values of hydraulic resistances of sections and absolute values of flow rates in them, t/h. Modeling of an emergency situation in some state s of the system is performed by excluding a component whose failure corresponds to this state from the calculation model of DHS.

3.5. Formalization of a problem of determination of optimal reliability parameters of DHS components

The values of average reliability parameters determined by expressions (15)–(20) are distributed among the system components according to the following equations of conservation of the sum of system state probabilities:

$$\overline{\lambda}_j \sum_{s\in E} p_s = \sum_{n\in N}\ \sum_{s\in E(n)} \lambda_n p_s,\ j \in J; \tag{26}$$

$$\overline{\mu}_j \sum_{s\in E} p_s = \sum_{n\in N}\ \sum_{s\in E(n)} \mu_n p_s,\ j \in J. \tag{27}$$

Here: p_s is probability of system state s; n is number of system component; N is a set of system components; $E(n)$ is a subset of system states to which the system can transition because of failure or restoration of component n; λ_n, μ_n are failure or restoration rates of component n, 1/h. The probabilities of system states are determined by solving the *markov random process* equations describing a sequence and structure of events that characterize the DHS operation. The use of the markov processes for reliability analysis of a considered object is justified by a large number of applications of this mathematical tool for studying the reliability of various energy systems. The methodological issues related to the application of markov random processes for reliability analysis of DHS subsystems (HS and HN) are discussed in [22, 25–29]. The studies discussed in [30–33] apply the markov models for the comprehensive analysis and optimization of the DHS reliability, considering all stages of the technological process of thermal energy production and distribution.

Stationary markov model of DHS operation can be represented by the following system of linear equations:

$$p_s\left(\sum_{n\in N(s)} \lambda_n + \sum_{n\in N(s)} \mu_n\right) = \sum_{z\in E(s)}\left(\sum_{n\in N(z)} p_z\lambda_n + \sum_{n\in N(z)} p_z\mu_n\right),\ s \in E. \tag{28}$$

Here: p_z is probability of system state z (division of state into s and z is necessary to write the system of equations of random process); $N(s)$ is a subset of system components whose failure or restoration corresponds to a direct transition of the system from state s to some other state z; $N(z)$ is a subset of system components whose failure or restoration corresponds to a direct transition of the system from state z to some other state s; $E(s)$ is a subset of the system states from which the system can transition to s.

According to the problem stated in point 3.1, the objective function of DHS reliability optimization is expressed as a sum of costs required to ensure the values of reliability parameters of the DHS components:

$$F_{\text{obj}} = \sum_{n \in N} f_{n\lambda}(\lambda_n) + \sum_{n \in N} f_{n\mu}(\mu_n). \quad (29)$$

Here: $f_{n\lambda}(\lambda_n)$, $f_{n\mu}(\mu_n)$ are cost functions of ensuring reliability parameters of components, i.e., their failure and restoration rates respectively, EUR. The type of functions (29) and their quantitative parameters are determined by the methods of approximation on the basis of an analysis of the actual data on the cost of equipment with different reliability characteristics, costs of installing the backup components; costs of establishing and maintaining the emergency and restoration services, and other measures capable to improve the reliability.

Technically possible values of reliability parameters of the components are specified by the following constraints:

$$\lambda_n^{\min} \le \lambda_n \le \lambda_n^{\max}, n \in N; \quad (30)$$

$$\mu_n^{\min} \le \mu_n \le \mu_n^{\max}, n \in N. \quad (31)$$

Thus, the optimization problem of DHS component reliability, given prosumers, lies in the following:

Minimize function (29) under the following conditions and constraints:

1) conditions (15) – (20), which determine the relations between average reliability parameters of DHS components in terms of the prosumer functions (21), (22);
2) conditions (23) – (25) according to which the levels of heat supply under different system states are calculated;
3) conditions (26) and (27), which determine the principles of allocating the average reliability parameters among the system components;
4) condition (28), which determines the probabilities of states by solving equations of the markov random process;
5) constraints (30) and (31) on the reliability parameters of components.

The nonlinearity of the considered optimization problem is connected firstly with function (29), which is usually a power function. Such problems are solved by the iteration methods using the GAMS and Maple software as solver.

IV. Computational Experiment

The computational experiment is conducted for the DHS diagram presented in Fig. 2a. The diagram consists of two district heat sources (HS1 and HS2), seven consumers (nodes 1–7), and a looped HN consisting of 18 sections (branches). The overall heat load of DHS is 2 341 GJ/h, and the total capacity of district sources is 2 717 GJ/h. One of the consumers is a prosumer (P7) with a load of 400 GJ/h and HS with a capacity of 200 GJ/h. HS2 supplies heat to P7 according to the hydraulic calculation of the system. Therefore, the problem of optimal management of HS load distribution is solved at the level of interaction between these entities. Figure 2b demonstrates a scheme of their interaction according to the above-described approach and model. P7 is assumed to have its HS running on fossil fuel, for which a power cost function with corresponding approximation coefficients is given. Diagrams of HS1 and HS2 are the same and are shown in Fig. 2c. These diagrams consist of the main aggregate components: boiler 19, turbine 20, network heaters 21 and 23, and network pumps 22 and 24. The indicated component numbers correspond to HS1, the assigned numbers for HS2 are from 25 to 30.
The optimal loads for HS2 and P7 in the considered DHS diagram during the entire heating period of 6 000 h with a step of 1000 h are illustrated in Fig. 3a. This diagram shows the heat load curves of P7 with highlighted amounts of heat generated by HS2 and HS of P7. According to Fig. 3a, HS of P7 operates during the time of consumer peak loads and supplies heat in the amount of about 180 GJ/h. The total heat consumption of P7 during the heating period is 1 026.5 thousand GJ, including 890.7 thousand GJ (86.8%) from the district HS2, and 135.9 thousand GJ (13.2%) from self-generation. The economic effect of the P7 source operation can be seen in Fig. 3b. Its value corresponds to the area of a solid figure of orange color and equals EUR 277 thousand or 7.6% of the total cost for the heating period.

A reliability study of the considered system is based on a joined diagram of the heat network (a set of sections) and district sources according to the comprehensive DHS reliability analysis approach presented in [30–32]. The random process of the DHS functioning is modelled under

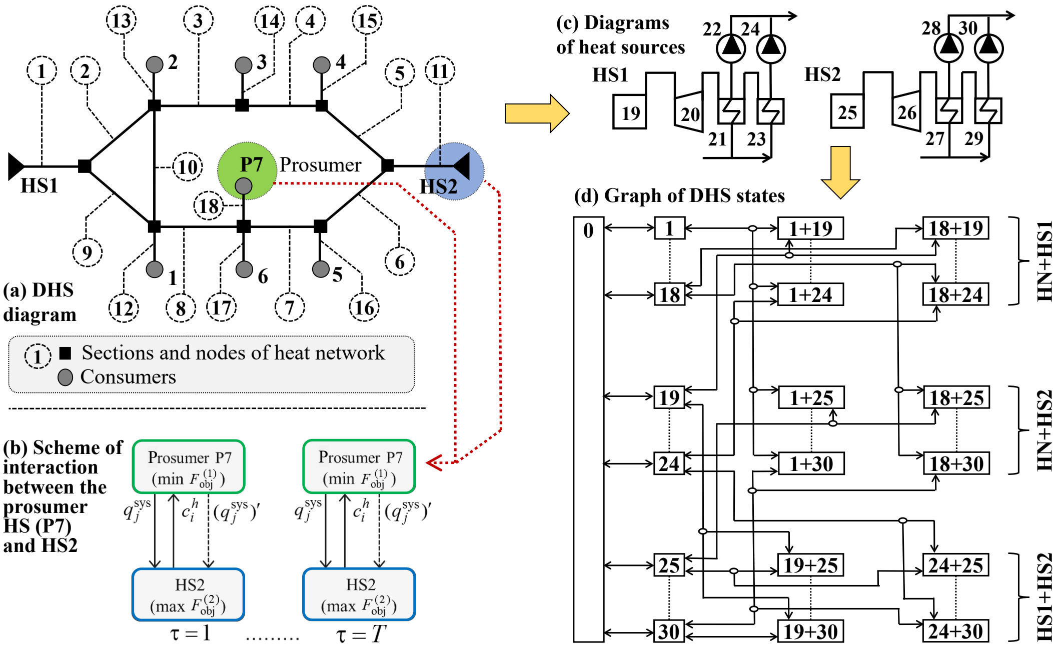

Fig. 2. Illustration of the computational experiment: (a) general diagram of tested DHS; (b) scheme of bi-level interaction between the prosumer HS (P7) and the district HS2; (c) principal diagrams of district HS1 and HS2; (d) graph of DHS states and transitions between them.

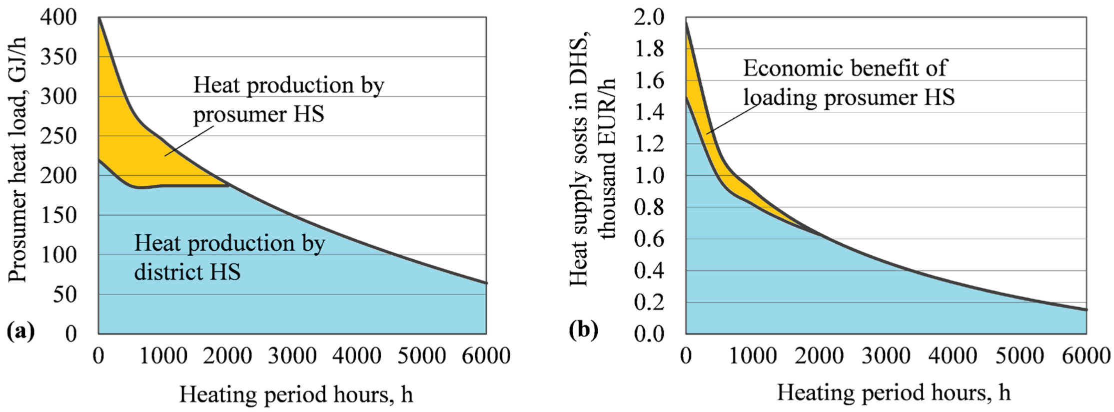

Fig. 3. Results of the optimal management of considered DHS with prosumer: (a) economically optimal load of prosumer HS (P7) and district HS2 during the heating period: (b) a graph of heat production costs in DHS with benefit of prosumer P7.

the condition of simple flow of events (Poisson flow), and the formation of a set of states is limited by consideration of the joint failure of no more than two components from different DHS subsystems (HN, HS1, and HS2). The oriented graph corresponding to this structure of states and transitions between them is shown in Fig. 2d. The state numbers on the graph correspond to the failed components in accordance with the diagrams in Fig. 2a and Fig. 2c. The probabilities of these states are determined by solving a system of 283 equations of the markov process of form (28). Optimization of the reliability parameters of system components is carried out when the following normative (required) values of the nodal reliability indices are met [22]: AF = 0.97 and FOP = 0.905. The ranges for possible values of the optimized reliability parameters of system components are set as follows: failure rate is 0.0002–0.0025 1/h; restoration rate is 0.007–0.09 1/h. Power-law functions of costs for ensuring reliability parameters, which form the objective function (29), were obtained on the basis of approximation of reference data on the structure and unit cost of reserved components, and the emergency services [22].

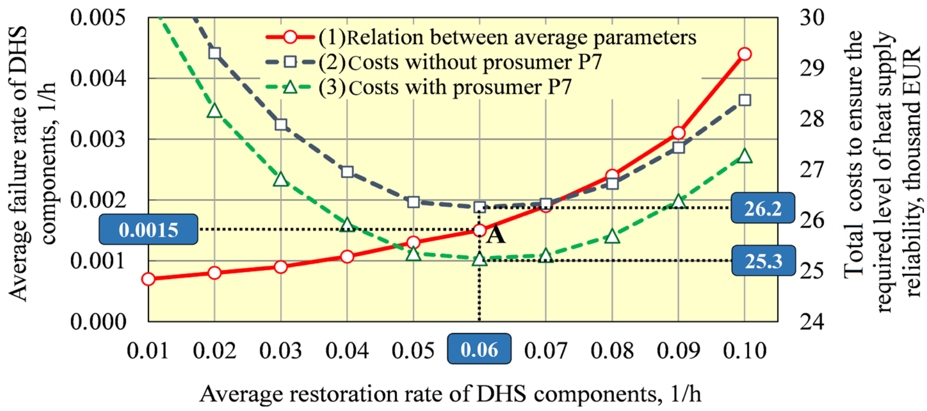

Fig. 4. Results of ensuring reliability of DHS with prosumer: optimal relation between average (integrated) reliability parameters of system components (failure and restoration rates) to fulfill the requirements for the reliability indices at minimal reliability cost.

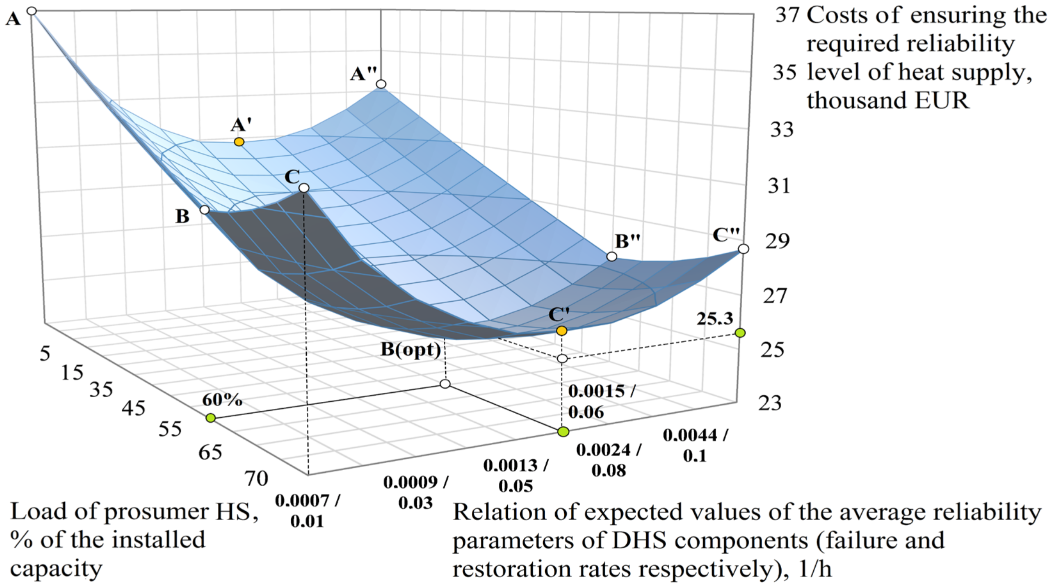

Fig. 5. Results of a comprehensive reliability study for prosumer functioning in DHS: relation between reliability parameters of system components (failure and restoration rates) and costs of ensuring the required reliability level of heat supply depending on the load of prosumer P7 source.

Figure 4 shows the result of search for the optimal relation of the average (integrated) reliability parameters of system components (graph 1), which correspond to the minimum costs of ensuring the reliability of the system when performing the required reliability indices (AF and FOP). Graphs 2 and 3 in Fig. 4 present the change in the costs of ensuring the required level of reliability with and without considering the functioning of P7 source respectively. The obtained solution at point A corresponds to the following values of average (integrated) reliability parameters: failure rate – 0.0012 1/h, restoration rate – 0.048 1/h. These values of integrated parameters are distributed over the system components according to equations (26) and (27) in the following ranges of values: 0.0004–0.0016 1/h for failure rate and 0.025–0.07 1/h for restoration rate. The cost of ensuring reliability is EUR 26.2 million without reserve of P7 source and EUR 25.3 thousand with reserve of P7 source. The economic effect from the use of reserve by source of P7 in the system is EUR 0.9 thousand or 3.4%.

Figure 5 illustrates a search for an optimal reliability solution for DHS given the use of capacity and time reserve of the prosumer HS (P7). This diagram shows the relation between reliability parameters of DHS components (failure and restoration rates) and costs of ensuring the required reliability level of heat supply depending on the load of P7 source. The obtained solution at point B(opt) corresponds to the costs necessary to ensure reliability in the amount of EUR 25.3 thousand with a determined relation of expected values of reliability parameters (failure rate is 0.015 1/h and restoration rate is 0.06 1/h) and loading for the P7 heat source at the level of 60%.

The results obtained allow outlining some features of the prosumer functioning in the heating system. In particular, we can conclude that the most effective area of distributed HS application corresponds not to the full coverage of consumer loads but to the level of 60–80% (depending on the reliability requirements). This provides a decrease in the consumer load on the system and compensates for the lack of thermal energy under emergency conditions in the system (in case of a failure of the system components). Both of these significantly increase the reliability of heat supply to prosumers themselves and the reliability of the entire system, embracing consumers that do not have heat self-generation and other active reserves. In addition, during the period of maximum heat loads (at minimum outside temperatures), the prosumer HS can operate as a peak source, reducing the load on district heat sources and lowering the likelihood of emergency conditions associated with failure of equipment operating at limiting operating parameters in such periods.

V. Conclusion

The significance of the studies on heat prosumer is related to the objective problems in heat supply, including low cost-effectiveness of operating DHS and insufficient quality and reliability of heat supply to consumers. This research states the load management problem of DHS with prosumers. Solving this problem is aimed at the cost-effective distribution of heat sources to supply heat to consumers from both district heat source and prosumer-owned heat source. A mathematical tool of bi-level programming is used to solve this problem. The second research problem is formulated to ensure DHS reliability considering the prosumer functions as a way to provide additional capacity and time reserve owing to the prosumer heat source. This problem is solved using nodal reliability indices, markov random process, some basic laws of cogeneration, and others.

The scientific novelty of the conducted research lies in the following:

1) The problem of managing the joint operation of district heating system (DHS) and distributed prosumer heat sources (HSs) within the DHS was formulated for the first time as a bi-level optimization of the heat load of these sources;

2) A principle of the most rational solution (equilibrium) for the distribution of heat loads of district HSs and distributed prosumer HS in DHS was proposed based on a three-stage cycle of strategies of the heat market actor;

3) A bi-level mathematical model was developed to optimally manage joint operation of district HS and distributed prosumer HS in DHS (loading of district and distributed sources) based on technical and economic criteria;

4) The bi-level mathematical model was modified to a single-extreme optimization problem, which simplifies the calculations;

5) The problem of ensuring the DHS reliability in terms of the redundancy functions of prosumer (mainly by its sources) is formulated, which involves searching for an optimal relation of the active power reserve of the prosumer's sources and the functional reserve of the system (component reliability);

6) A technique is proposed for ensuring reliability, based on various methods and models: models of markov random processes, methods of the theory of hydraulic circuits, analytical expressions describing the change in heat loads, the processes of accumulating thermal energy (thermal inertia), etc.;

7) The mathematical model is obtained to determine the average (integrated) reliability parameters of system components, ensuring the requirements for the reliability indices of heat supply to consumers, given the factors specified above in point 6.

The main advantage of the model designed to optimally manage the jointly functioning district HSs and distributed prosumer HS in DHS (point 3), in comparison with the existing developments, is the comprehensive consideration of various technical and economic aspects of the studied systems operation, including thermo-hydraulic conditions in the network (flow distribution), operating costs for the production and distribution of thermal energy in the system, change in heat loads during the design period, and some others.

The main advantage of the proposed methods for ensuring the reliability (point 6) lies in the integration of measures aimed at reducing the failure rates and enhancing restoration rates of the components in a joint procedure of search for reliability parameters, which makes it possible to most rationally distribute the overall potential enabling the increase in reliability of DHS components. The practical applicability of the developed methods for optimization of reliability parameters of DHS components is confirmed by the calculations carried out on a test diagram.

The results obtained in the calculation for the test DHS diagram show the operability of the developed mathematical model and the possibility of gaining the economic and reliability effect owing to the use of the prosumer heat source. Further research in this area will provide a more informed assessment of the effectiveness of the prosumer involvement in district heating related to economical and reliability.

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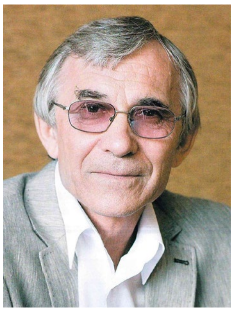

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The Use of Energy Storage to Improve Controllability and Security of the Belarusian Power System

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Abstract — **The planned commissioning of the second unit of the Astravets nuclear power plant in the Republic of Belarus in 2023 will exacerbate the need to ensure controllability and security of both the entire Belarusian power system and its individual power generation centers. To address this issue effectively, it is crucial to flatten the load curves of electricity consumers, and energy storage systems (ESS) make this achievable. The Belarusian power system can use several types of ESSs, both system-wide and local. Li-ion-based ESSs have the best performance when used to smooth the load curves of individual substations. This paper assesses the efficiency of lithium-ion energy storage units. The assessment focuses on various factors such as leveling of the daily load curve of the consumer, decrease in power loss, and voltage regulation at the ESS installation site.**

Index Terms: **Power system, nuclear power, energy storage system, daily load profile.**

I. Introduction

The fundamental concept driving the power system design is simultaneous and synchronized power generation and consumption. This condition makes it possible to maintain one of the most important operating parameters, which is AC frequency.

The daily load curve of both the entire Belarusian power system and its individual power generation centers is characterized by significant irregularity with pronounced daytime load peaks and demand troughs at night. The irregularity factor of the daily load curve is 0.65–0.7.

When the second unit of the Astravets NPP is put into commercial operation in 2023, the power of the two base load units operating in the Belarusian power system will amount to about 40% of the maximum load of the power system. The number of powerful flexible units of condensing power plants (CPPs) running in hot standby should be reduced to maintain the self-balancing state.

The introduction of ESSs into the power system will separate the power generation and consumption processes in time (provided that ESS efficiency is high) and smooth out the load curve of individual power generation centers and the power system as a whole. Addressing this problem will make ESSs a key component of the electric power industry in the context of “smart energy concept.”

Potential ESS applications in the power system also include voltage and frequency regulation, provision of spinning capacity, emergency power supply to prevent the unfolding of system accidents (in the event of power system islanding), restoration of the power system after an accident, and emergency power supply to the consumer. A unique benefit of using ESSs is that they can perform the above functions simultaneously [1].

It is worth noting that renewable energy sources (RES) have not be-come widespread in the Republic of Belarus (the share of renewable generation in the installed capacity of the Belarusian power system is about 3%). The use of

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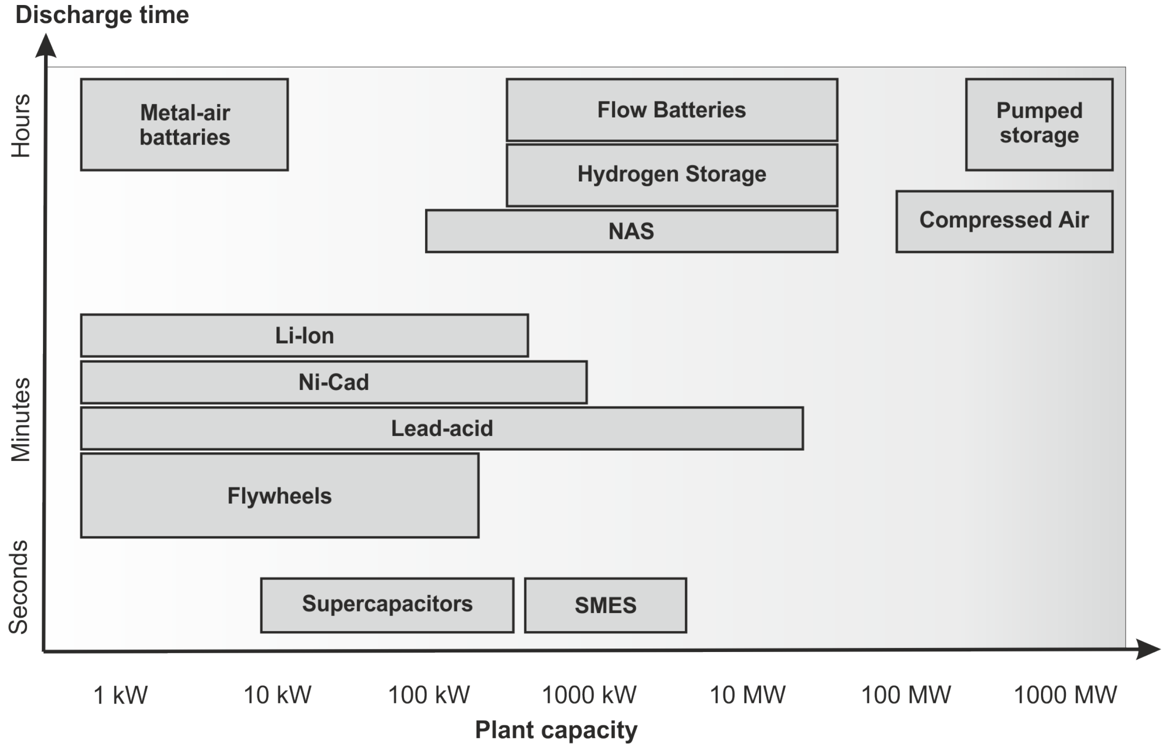

Fig. 1. Capacity and discharge time (duration) of various ESSs.

ESSs, however, is a key solution for efficient integration of renewables into the power system.

II. Review of the Worldwide Experience in the Use of ESSs

Energy storage systems have been used in the world for quite some time. For example, galvanic cells were invented in the 1800s and the first pump storage projects were introduced in the early 1900s.

Recently, the demand for ESSs has increased dramatically. This is due to the digitalization of control systems of the power system and its local power generation centers; higher electrification in various sectors of the economy, including transport; decentralization of electricity generation (large-scale use of distributed generation, including RES), and introduction of multifunctional energy facilities (cogeneration plants).

In the Belarusian power system, where installed capacity of the Astra-vets NPP is significant, an urgent task to be addressed by the use of ESSs is to flatten irregular daily load curves. ESSs can be used to supply consumers with electricity during the time of the day when power consumed exceeds power generated by the economically feasible generation equipment (NPPs, large units of TPPs). Another use of ESSs is to store electric energy during the periods when its generation at sources at issue exceeds consumption (which calls for the generation equipment shut-down). Furthermore, ESSs reduce the need for a steep increase or de-crease in the load of generation equipment in case of emergencies in the power system.

To assess the efficiency of ESSs utilization, one should factor in their energy capacity, maximum power output during the discharge period, dis-charge duration, and storage efficiency.

Known energy storage technologies can be divided according to the type of energy stored:
- mechanical (pump storage systems, flywheels),
- electrochemical (rechargeable cells, flow batteries),
- chemical (fuel cells),
- electrical (capacitors, supercapacitors, superconducting magnetic energy storage systems),
- thermal (use of molten salts and hot water).

Depending on the technology, the duration of energy storage can range from less than 10 hours (some battery storage systems) to weeks, months, and years (pump storage systems).

Figure 1 summarizes the data on capacity and discharge time (duration) of ESSs based on various technologies [2].

Table 1. Main Specifications of Major Energy Storage Technologies

Technology	Energy density, Wh/l	Power density, W/l	Nominal capacity, MW	Life cycle, number of charges and discharges	Storage time
Flywheels	20–80	5,000	<20	>100 000	ms – 15 min
Compressed air energy storage technology	12	0.2–0.6	100–300	>13 000	30 s – days
Pumped storage	0.2–2	0.1–0.2	100–5 000	>100 000	1 h – days, months
Capacitators	0.05–10	100 000	0.05	>50 000	ms – 1 h
Battery storage	15–1 673	10–10 000	0-100	1 000–20 000	s – days
Flow batteries	10–70	0.5–33.42	0.03-50	12 000	h – months
Superconducting magnetic energy storage	6	2 600	0,01-10	100 000	1 ms – 1 h
Hydrogen	600	0.2-20	<50	>1 000	s – days
Supercapacitors	10–30	40 000–120 000	0.01–1	>100 000	1 ms – 1.2 h
Fuel cells	500–3 000	>500	50	>1 000	s – days
Thermal energy storage	120–500	-	0.1–300	≈13 000	min – month

Table 1 presents main specifications of major energy storage technologies [2].

III. ESS Technologies Implementable for the Belarusian Power System

Considering the level of development of ESS technology and maturity of the industrial prototypes in the CIS countries, we can conclude that only some of the ESSs mentioned above can be integrated in the Belarusian power system.

As already noted, the commissioning of the Astravets NPP has exacerbated the issue of peak shaving and valley filling in the daily electric load curve of the Belarusian power system, since the NPP units normally operate to meet the base-load demand. A conventional solution to this problem is to construct a pumped storage power plant (PSPP) together with the NPP. PSPPs are both highly flexible sources of peak power and serve as controlled loads. They prove effective when utilized:

- to do peak shaving;
- to provide multiple short-term pickups of the system load;
- to raise the nighttime load of TPPs to the level optimal in terms of their operational reliability;
- to ensure a fast-acting backup power for maintaining frequency and a short-term backup power during emergencies;
- to control the reactive power balance in the network.

In Belarus, due to the specific features of its terrain and the need to flood large areas, the unit capacity of PSPPs is limited to 400–570 MW. Therefore, the construction of several such plants is required to provide reliable backup power for two 1200 MW units of the Astravets NPP. Furthermore, this infrastructural solution requires significant capital expenditures and a long time to implement it, which is not feasible in the current context.

The global power industry has shown a remarkable interest in utilizing lithium-ion batteries, as evidenced by the widespread adoption of ESSs because they have better

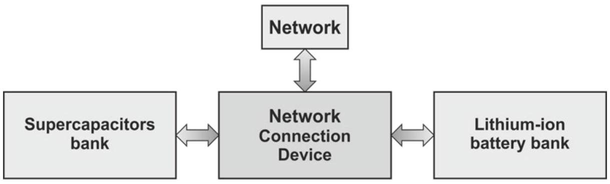

Fig. 2. Flowchart of a hybrid ESS.

performance compared to other storage battery technologies. Li-ion battery is gaining popularity in power generation and other sectors due to its long service life, high cell voltage, excellent performance in low temperatures, sufficient charge retention, and the desired depth of charge.

Another promising strand is the use of supercapacitors as part of "hybrid" ESSs together with storage battery [3].

Hybrid energy storage devices perform the following functions:

- flatten load curves in the network (by storing electric power during power-surplus periods and delivering it to the network during power-deficient periods);
- ensure increased steady-state and transient stability limits when coupled with modern power electronics devices;
- damp active and reactive power fluctuations, eliminate or significantly reduce irregular fluctuations in tie lines, and thus increase the transfer capability of the transmission line;
- ensure uninterrupted power supply to substations and electrical networks (auxiliaries), and to the essential consumers;
- provide stable and sustainable operation of decentralized and non-conventional sources operating both off-grid and as part of an IPS.

In hybrid ESSs, lithium-ion batteries are used as long-term energy storage, while banks of stacked-type supercapacitors are used as short-term energy storage.

Figure 2 shows the flowchart of a hybrid ESS.

In 2022, a draft "Concept of Application of Energy Storage Systems Based on Lithium-Ion Batteries in the Belarusian Power System" was developed. The document envisages commitment to a full-fledged adoption and use of ESS at Belenergo's generation sources, in electrical networks, and at power facilities of industrial enterprises and transport.

According to the draft Concept, the technically available potential for installation of ESSs in the Belarusian power system is estimated for the sites of location at:

- 1 200 MWh and 150 MW for thermal power plants;
- 500 MWh and 100 MW for distribution systems of industrial consumers;
- 500 MWh and 70 MW for renewable energy sources;
- 2 800 MWh and 300 MW for charging infrastructure for electric vehicles.

IV. The Use of ESSs in 110 kV Distribution Networks of the Belarusian Power System

In 2022, RUE Belenergosetproekt did research to assess the technical capacity and feasibility of installing lithium-ion energy storage units with a view to flattening daily load curves, reducing power loss, and regulating voltage at the point of ESS installation.

Several substations with transformer utilization rate close to 50% in normal operating conditions were selected as "standard" 110/10 kV substations (SS). It is worth noting that the share of substations with such a significant transformer load in the Belarusian power system is less than 5%, and they are located near the capital city, large regional centers, and in major industrial hubs of the Republic of Belarus. However, due to the policy of increasing electricity consumption for heating and hot water supply, which is pursued in the Republic of Belarus, the stated power of both residential and industrial consumers is expected to grow in the years to come. This will entail the need to address the problem outlined below. ESS performance was tested for two alternative options for the case of increased electrical load at the substations:

- reconstruction with transformer power increased;
- installation of ESS to shave daily load peaks and keep existing transformers in operation without overloading.

The input data included:

- reporting measurements obtained from automated metering system (half-hourly load snapshots) for transformer windings of a given substation during four representative days (winter/summer, weekday/weekend);
- electric loads according to the current technical conditions issued for power supply to consumers from this substation;
- flow diagram of the substation and feeding network.

The Korzyuki substation of RUE Minskenergo was chosen as a "standard" 110/10 kV substation with predominantly residential loads.

A notional substation was simulated as a "standard" substation with predominantly industrial loads.

Two 110/10 kV transformers with a capacity of 16 MVA each were in-stalled at the 110 kV Korzyuki substation.

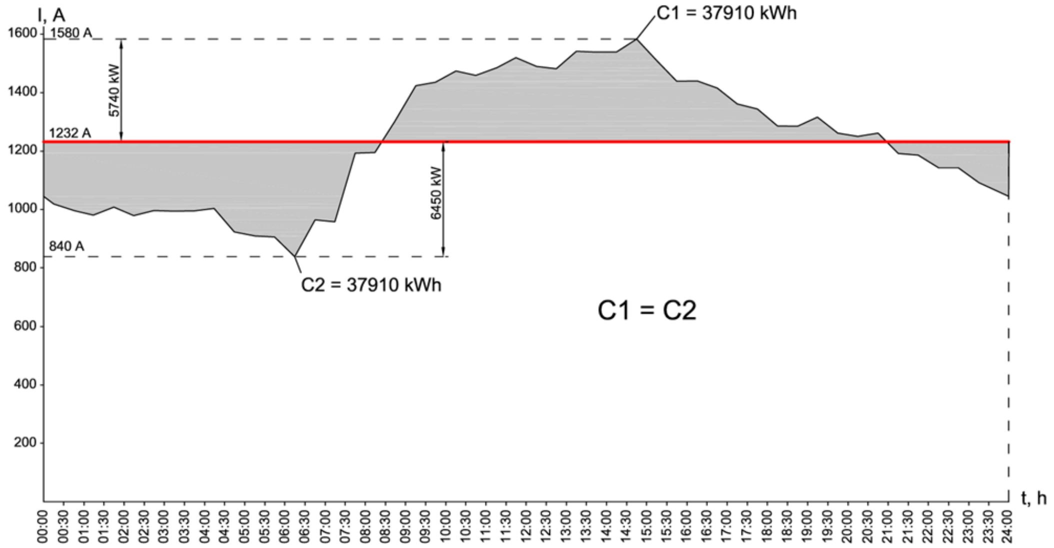

Fig. 3. Daily load curve (load current, A) of the 110/10 kV Korzyuki substation on a winter weekday, given the equality of ESS discharge/charge areas.

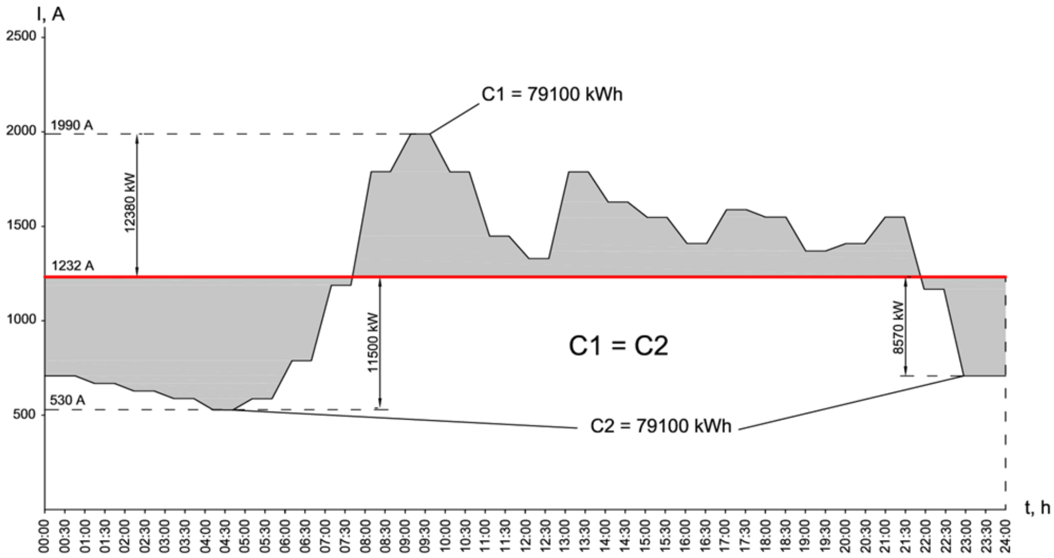

Fig. 4. Daily load curve (load current, A) of the 110/10 kV substation serving the woodworking industry on a winter weekday, given the equality of ESS discharge/charge areas.

Figure 3 shows the simulated daily load curve of a winter workday for this substation. This simulation factors in the increase in load under equal areas of battery discharge/charge that makes the application of ESS possible. The allowable maximum load exceeds the substation capacity limit by 28%. The required operating capacity of the battery should be about 38 thousand kWh and the nominal capacity should be 6.5 MW.

The horizontal line of the graph indicates the overload limit of the sub-station capacity (40% or 1 232 A) with one of the transformers removed from service for maintenance or shut down due to emergency.

The comparative calculations of costs for the options of modernization of the 110/10 kV Korzyuki substation (replacement of transformers versus ESS installation) demonstrated that capital expenditure incurred in the installation of the 10 kV ESS exceeds the cost of transformer replacement by a factor of 12.

This study does not consider 110/10 kV substations serving predominantly industrial loads and enterprises

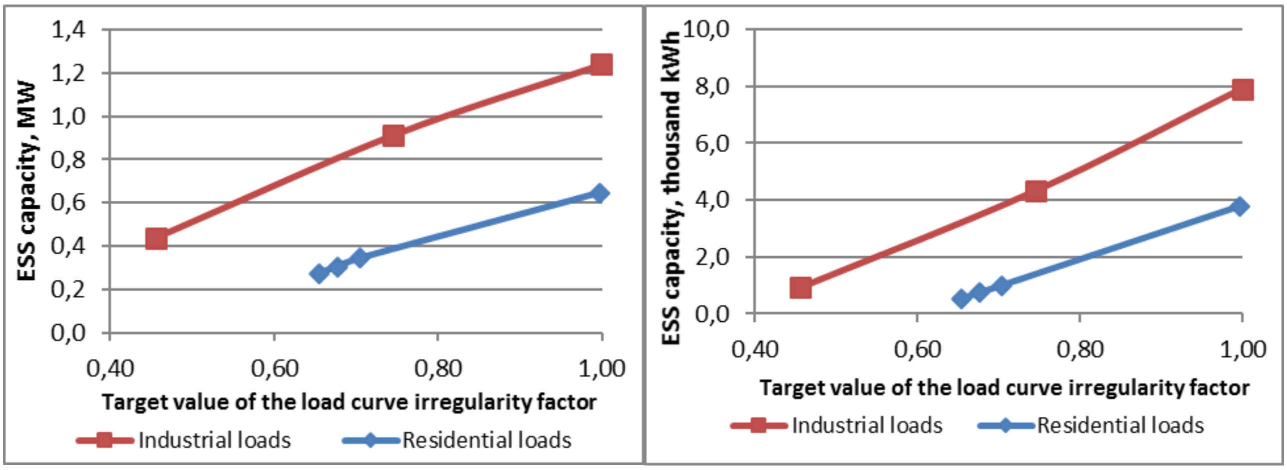

Fig. 5. Relationship between the required power and capacity of the ESS and the target value of the load curve irregularity factor.

operating continuously (oil refining, metallurgy, heavy engineering, etc.), since their daily load curve has no pronounced peaks and troughs in power consumption, during which the storage unit could be charged/discharged. Installing ESSs at such substations for reducing peak loads is not feasible. This does not preclude the installation of ESSs for the reasons of reliability of power supply to the essential units of the production process of this type of enterprises.

A 110/10 kV substation of the woodworking industry with two 16 MVA transformers was used in our case study as a substation serving predominantly industrial loads. Figure 4 shows the load curve for such a substation with equal areas of battery discharge/charge, at which ESS proves feasible.

The allowable maximum load exceeds the substation power limit by 62%, the required operating capacity of the battery is about 79.0 thousand kWh at the nominal capacity of 11.5 MW.

The comparative calculations of costs for the options of modernization of the 110/10 kV Korzyuki substation serving the woodworking industry (replacement of transformers versus ESS installation) show that capital expenditure incurred in the installation of the 10 kV ESS exceeds the cost of transformer replacement by a factor of 26.

We performed a series of calculations for substations with two characteristic load curves. The calculations indicated that to fully flatten the load curves, it will be necessary to install ESSs of sizable power and capacity: 12 MW and 80 thousand kWh, respectively (Fig. 5).

V. Power Loss in the Network Due to ESS Installation

Assessment of the impact of ESS on power loss involved calculations of changes in power loss in the network of the Minsk power system with the voltage of 10 kV and more for the time frame covered by the options considered:

- Option 1: the use of an ESS and a transformer of a smaller power (16 MVA);
- Option 2: the use of a transformer of higher power (25 MVA).

The calculations were performed using the RASTRWIN software.

Additional annual power loss ΔW in the network of 10 kV and higher were determined by the equation

$$\Delta W = \Delta P \cdot \tau, \quad (1)$$

where ΔP is additional added power loss in the network of 10 kV and above due to increased load (with no ESS); τ is time of maximum loss determined by the equation

$$\tau = (0.124 + T_{\max}/10000)^2 \cdot 8760. \quad (2)$$

Here $T_{\max}$ is time of maximum load utilization, which was assumed to be equal to 5 000 h.

Power loss by transformers was calculated as follows:

$$\Delta W_T = \Delta P_{XX} \cdot 8760 + (S_{\max}/S_{\text{nom}})^2 \cdot \Delta P_{SC} \cdot \tau, \quad (3)$$

where ΔP_{XX} is the no-load loss of the transformer; ΔP_{SC} is the short-circuit loss of the transformer; $S_{\max}$ is the highest value of the total power running through the transformer;

S_{nom} is nominal power of the transformer.

Power loss by the 10 kV ESS was determined based on the overall efficiency of lithium-ion energy storage units, which is about 85% according to the data of manufacturer. Analysis of the calculation results indicated that in the case of using ESSs, their power loss and the increase in load loss in transformers of smaller power under Option 1 were not offset by the reduction in no-load loss in transformers of smaller power under Option 2. Therefore, in general, power loss was greater with the installation of ESSs than without their use, which needs to be taken into account in the feasibility study.

VI. Use of ESSs for Voltage Regulation

We calculated the effect of a 6.5 MW ESS on voltage levels in the 10 kV network of the 110 kV Korzyuki substation. 10 kV ESS inverters are selected so as to generate the necessary reactive power for voltage regulation in the 10 kV network. With a load power factor of 0.9, the power of the inverters will be about 7.2 MVA. According to the ESS nameplate data, the power factor control range is 0.1 to 1 per unit, provided the inverter is not loaded with active power. Thus, a 7.2 MVA inverter can control reactive power in the range of – 6.5 MVar to + 6.5 MVar.

A change in reactive power by 6.5 MVar on 10 kV busbars for the 110 kV Korzyuki substation leads to a change in the voltage level of the 10 kV network by 0.6 kV. When utilizing the full regulation range, the 7.2 MVA inverter can regulate the voltage over a range of 1.2 kV (about 12%).

The 10 kV ESSs are mainly used to avoid overloading of 110 kV substation transformers when one of two 110/10 kV transformers is shut down during the winter season while substation loads are significant. When operating two transformers during the same period or in the case of summer loads, the active power of ESS will not be fully used. This allows utilizing these devices as means of voltage regulation (generation/consumption of reactive power) in a 10 kV network when active power consumption/generation is below the nominal value of the plant.

The technical feasibility of reactive power generation/consumption can only be determined after calculating the required level of inverter loading with respect to active power for specific loading conditions of the substation. It is also important to highlight that for voltage regulation on the 10 kV side, 110/10 kV transformers are equipped with on-load tap changers (OLTC), therefore, the use of ESSs for 10 kV voltage regulation is not a top priority.

According to preliminary estimates, cutting down the ESS costs to be-low 200 USD/kWh can serve as a criterion of economic feasibility of large-scale adoption of ESSs in 10–110kV distribution systems of the Belarusian power system. In so doing, one should take into account such factors as ESS service life and degradation, and the payback period of ESS as an energy-saving measure should not exceed 10 years.

It is worth noting that the feasibility study of the ESS in 10 kV distribution networks of industrial enterprises should involve [4]:

- identifying special requirements for the reliability of process equipment in operation at the enterprise;
- clarifying estimates of the economic benefit based on additional terms of contractual relations with the power supply entity (payment for stated power, participation in demand response, frequency regulation, etc.).
- clarifying the costs of the devices planned for installation and their maintenance costs.

VII. Conclusion

1. The use of ESSs at the 110/10 kV substations offers a solution to balance daily variations in electricity demand. By compensating for daytime peak loads and boosting the nighttime minimum loads (load “valleys”) ESSs help level out the load curve and avoid the replacement of 110/10 kV transformers with higher power transformers.

2. ESSs can be used for voltage regulation in the 10 kV substation network, however, since 110/10 kV transformers with on-load tap-changers are used, the task is not of primary importance.

3. The cost of ESS installation significantly exceeds the cost of reconstruction of electrical network facilities, which precludes us from drawing a definite conclusion about the feasibility of large-scale adoption of ESS in 10 kV distribution networks.

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A Brief Analysis of Topics of the IEEE Conference on Energy Internet and Energy System Integration in 2017–2021

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Abstract — **This paper analyzes the bibliometric data of proceedings of the IEEE Conference on Energy Internet and Energy System Integration posted on IEEE Xplore in 2017–2021. The main objective of the study is to identify the current research issues related to the Energy Internet. To this end, Author Keywords, INSPEC Controlled Terms, and terms compiled from n-grams that were derived from titles and abstracts of conference papers are used to describe topical issues. The terms are clustered using VOSviewer, and the clustered terms serve as a description of current issues. Several research contributions relevant to the subject of this study are summarized to put the latter into a more task-specific context. The conclusion outlines topical issues that merit further, more in-depth, analysis.**

***Index Terms*: Energy Internet, Energy Systems, IEEE Xplore, bibliometric analysis, current research issues, VOSviewer.**

I. Introduction

Major international specialist conferences are of particular interest for identifying current issues within a particular research area. The topics of such conferences are carefully selected by their organizers, which is indispensable for attracting sponsors, industry representatives, and quality speakers to the conference. Conference proceedings are provided with homogeneous bibliometric data, which greatly simplifies their analysis. Decisions on whether publications are relevant to a subject under consideration involve experts, which proves more effective than selecting publications by keywords or filters when collecting materials for queries to abstract databases. Admittedly, special issues of journals have similar features, but it is very unlikely for a special issue to have several hundred articles. Furthermore, authors often use conferences in an attempt to showcase their new research, whereas what they generally choose to publish in special issues is more often the articles that succeed in addressing a particular problem.

The Institute of Electrical and Electronics Engineers (IEEE), which, according to Wikipedia is the world's largest association of engineers, with more than 423 000 members in over 160 countries, regularly holds international conferences on issues relevant to the industry and posts their bibliometric data on the IEEE Xplore platform for public access.

Due to the global trend toward energy transition, the complexity of energy systems increases, the number of their components gets larger, and the systems themselves become more diverse in terms of their specifications and operation. This contributes to the relevance of the task of maintaining the stable operation of such complex energy systems regardless of changes in weather conditions, faults of its individual components, and changes in consumption and generation.

Historically, the Internet served as a counterpart of such complex distributed systems because its resilience has been paramount to it since its inception. That sparked interest in the use of Internet resilience approaches developed in the course of Internet's operation. They were re-purposed to ensure the resilience of complex distributed energy

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systems. That is what underpins the surge of interest in the Energy Internet.

Given the growing interest in the topic of the Energy Internet, the IEEE has organized the annual IEEE Conference on Energy Internet and Energy System Integration (EI2) since 2017.

According to IEEE Xplore, the conference boasts the maximum number of publications among the 2021 periodicals having the term “Energy System” in their title:

- 2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2) → 797 publications;
- 2021 3rd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA) → 262;
- CSEE Journal of Power and Energy Systems → 224;
- Journal of Modern Power Systems and Clean Energy → 177;
- 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES) → 167.

This provoked interest in the bibliometric analysis of the proceedings of the conference in order to identify current research issues related to “Energy Internet and Energy Systems Integration”.

This study uses bibliometric data on conferences held in 2017 to 2021. At the time this study was initiated (November 1, 2022), data for the 2022 conference were not yet available as the conference was scheduled for November 11–13, 2022.

II. Materials and Methods

The bibliometric data used for identification of topical research issues were the conference proceedings metadata exported from the IEEE Xplore platform in the CSV format. Their breakdown by year was as follows: 2021→797; 2020→813; 2019→563; 2018→759; 2017→566 bibliometric records. There are, in total, 3 498 records for returned for the query: “Publication Title”: Conference on Energy Internet and Energy System Integration.

The aim of this study was not to perform a comprehensive bibliometric analysis of the topic in question. That is why issues of co-authorship, affiliation of authors, breakdown of publications by country, and other tasks were beyond the scope of the article.

We used VOSviewer [1] to build the co-occurrence network of terms and perform their clustering.

The data slices for more detailed analysis of individual components of the network were built using the data exported from VOSviewer.

One advantage that came with the bibliometric data of the conference was that the fill rate of the Author Keywords field was over 97%, which allowed us to use the terms of this field to build a co-occurrence network of terms and to cluster them so as to identify current issues within the research area in question.

Similarly, we used the following fields: IEEE Terms, INSPEC Controlled Terms, and INSPEC Non-Controlled Terms.

Additionally, a textual analysis of the “Document title” and “Abstract” fields was performed to identify key terms.

Since VOSviewer does not directly import data from the IEEE Xplore platform, the fields needed for our study were converted to the format of the fields as if they were exported from the Scopus system.

The total number of records used in the study was 3 478 (the previously specified value of 3,498 included explanatory fields).

Document Title; Authors; Publication Year; Abstract; DOI; Author Keywords; IEEE Terms; INSPEC Controlled Terms; INSPEC Non-Controlled Terms; Article Citation Count are the names of the fields stored for each publication.

Similar Scopus fields are Authors; Title; Year; Cited by; DOI; Abstract; Author Keywords; Index Keywords.

IEEE Terms; INSPEC Controlled Terms; INSPEC Non-Controlled Terms and terms obtained as a result of text mining procedures applied to titles and abstracts were used as Scopus indexed keywords.

III. Results and Discussion

A. *Author Keywords*

A total of 9 722 author keywords were identified, of which 1 641 occurred two or more times. We chose 500 terms with the highest total link strength to build the co-occurrence network. A larger sample makes the co-occurrence map of keywords difficult to read when presented in the form of the graph included in this paper. A smaller sample, however, tends to make the network and its clustering less detailed than necessary.

If the minimum cluster size is kept at 1, we get 21 clusters. This indicates that authors assigned keywords in an arbitrary fashion, i.e., the number of occurrences of keywords is large, but their co-occurrence is low.

With a minimum number of terms in a cluster being 60,

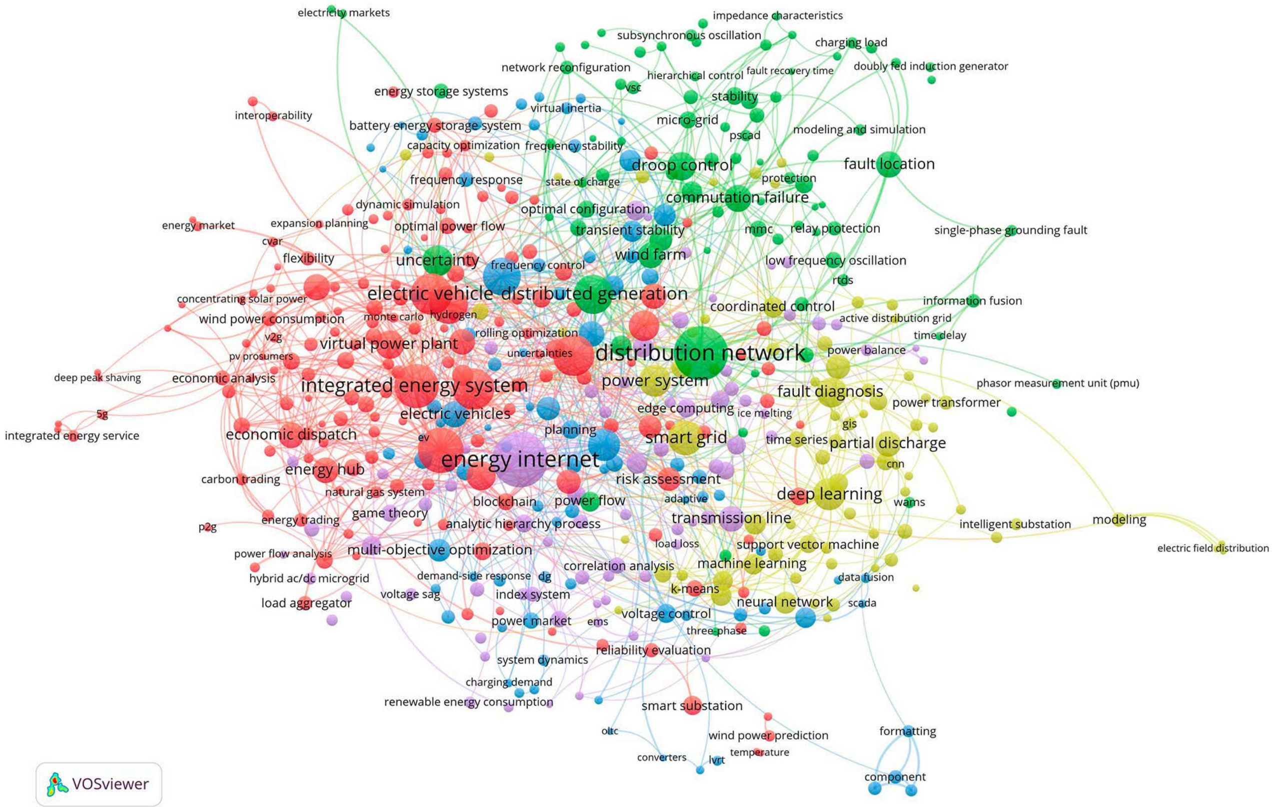

Fig. 1. Five clusters of Author Keywords co-occurrence graph for 3 498 records.

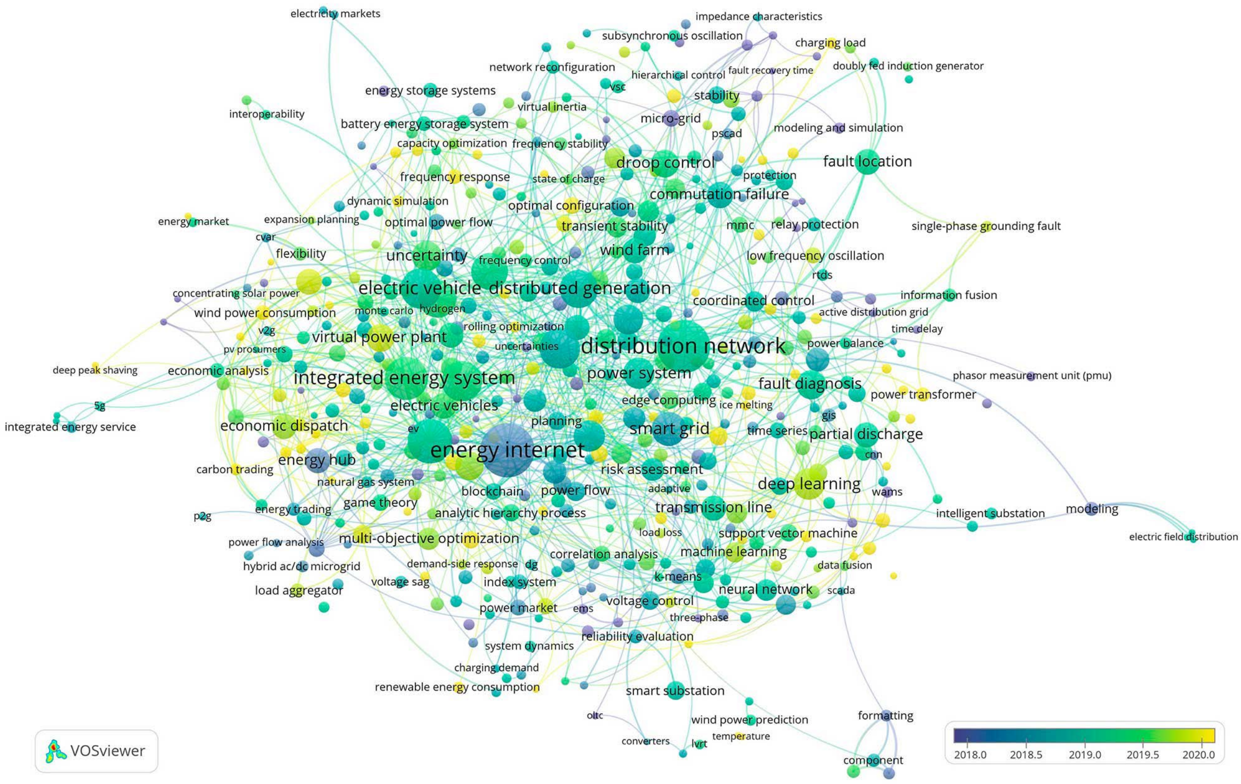

Fig. 2. Temporal variation of the Author Keywords co-occurrence network for 3 498 records.

obtained with a minimum number of terms in a cluster equal to 55 and 65. Therefore, this structure proved robust. The resulting network of five clusters is shown in Fig. 1.

The variation in the occurrence of Author Keywords over time is shown in Fig. 2.

The temporal variation of the Author Keywords shows that the term "Energy Internet" itself dominates the entire period from 2017 to 2021 and is not new.

Next, we will briefly analyze Author Keywords in each cluster.

Ten most frequent Author Keywords in the first cluster are: demand response: 74; integrated energy system: 71; microgrid: 62; renewable energy: 62; electric vehicle: 61; wind power: 54; HVDC: 34; electricity market: 32; virtual power plant: 30; robust optimization: 26.

This cluster topic can be described as follows: demand response electricity market based on integrated energy system, microgrid, virtual power plant, and robust optimization.

Renewable energy (renewable energy, wind power) and its applications (electric vehicle) are the focus of publications whose keywords were included in this cluster. It is worth paying attention to HVDC as the increasing role of power grids make the issues of their economic performance prominent.

To assess the shift in research interests over time, we compared the 10 terms with the highest average time of occurrence and the 10 terms with the average time of occurrence of an earlier period. The results are shown in Table 1.

The combination of the clearing model and reinforcement learning stands out in the first list.

The electricity market is a standard market with imperfect competition, where electricity suppliers earn higher profits through strategic bidding behavior. Ref. [2] reported a modified continuous automata algorithm with reinforcement learning to help electricity suppliers bid with limited information. In short, electricity suppliers and consumers submit their bids as part of the process, and the independent system operator (ISO) solves the economic dispatch problem to calculate the volume of electricity generation thus completing a round of the market clearing process.

10 most frequent Author Keywords in the second cluster: distribution network: 104; distributed generation: 56; uncertainty: 34; droop control: 30; commutation failure: 27; fault location: 26; wind farm: 25; vsc-hvdc: 19; dfig: 16; new energy: 16.

The topic of this cluster can be summarized as follows: distribution network, distributed generation and related issues: uncertainty, droop control, commutation failure, fault location. The results are shown in Table 2.

The terms in the first column of the table agree with the list of the most commonly used terms: optimal configuration, doubly-fed induction generator, charging load, fault identification, power flow distribution, transient overvoltage, model predictive control, and other terms that have become more common of late. They emphasize the importance of sustainable operation of complex systems, which is the root cause of the relevance of the Energy Internet as a research topic.

The list of the 10 most common terms in the third cluster: energy storage: 51; active distribution network: 38; electric vehicles: 26; control strategy: 24; unit commitment: 21; multi-objective optimization: 20; dc microgrid: 18; photovoltaic: 17; transient stability: 17; state estimation: 16.

Table 1. Ten Terms of the First Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
clearing model	vsc-mtdc
hydrogen storage system	profit distribution
shared energy storage	scenario reduction
dynamic simulation	two-stage optimization
hydrogen	power-to-gas
deep peak shaving	distributed energy system
frequency regulation market	natural gas network
high renewable penetration	uncertainties
pumped-storage hydropower stations	wind power integration
reinforcement learning	super capacitor

Table 2. Ten Terms of the Second Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
optimal configuration	three-phase
doubly-fed induction generator	time delay
charging load	weak grid
fault identification	micro-grid
power flow distribution	wams
transient overvoltage	cps
model predictive control	virtual impedance
load margin	simulation test device
low frequency oscillation	simulation test method
single-phase grounding fault	wireless communication

Table 3. Ten Terms of the Fourth Cluster with the Highest Avg. Pub. Year and Minimum Avg. Pub. Year.

Max avg. pub. year terms	Min avg. pub. year terms
voltage	user satisfaction
lithium-ion battery	formatting
frequency response	load shedding
equivalent model	styling
orderly charging	dynamic consistency
parameter identification	primary frequency response
sensitivity analysis	ev
incremental distribution network	decomposition
battery energy storage	dispatch
demand-side response	oltc

Table 4. Ten Terms of the Fourth Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year.

Max avg. pub. year terms	Min avg. pub. year terms
attack detection	kalman filter
digital twin	fuzzy theory
n-1 contingency	cnn
thermal aging	consumption
thermal inertia	multi-energy
loss	clean energy
modelling	modeling
non-intrusive load monitoring	active distribution grid
carbon emissions	transient stability assessment
low-voltage distribution network	urban energy internet

Note that this cluster often uses the term "electric vehicles", while the first cluster uses the term "electric vehicle". This is one of the problems with author keywords: different spelling/wording of terms otherwise close in meaning. Naturally, it is possible to lemmatize author keywords and even use synonyms, which is, however, a task in its own right. Clusters 1 and 3 share some similar topics, but while the first one focuses on demand and market, the terms in that cluster are more technical. The topic of the cluster can be summarized as follows: energy storage, active distribution network, electric vehicles, control strategy, unit commitment, multi-objective optimization. The results are shown in Table 3.

Even the types of energy storage differ from those in the first cluster: lithium-ion batteries and orderly charging in the former vs. hydrogen storage and pumped-storage hydropower stations in the latter. That is, one problem is how to perform optimal charging of the batteries, and the second is where to store the energy produced by renewable sources.

A list of the 10 most common terms in the fourth cluster:

smart grid: 45; deep learning: 37; power system: 37; fault diagnosis: 33; partial discharge: 25; simulation: 22; neural network: 18; load forecasting: 17; artificial intelligence: 16; coordinated control: 16.

In this case, the object of research are smart grid and power system, the current issues are fault diagnosis and partial discharge, and possible techniques to address them include load forecasting and coordinated control by artificial intelligence. Table 4 lists the terms that appear in newer and earlier publications.

The terms of the earlier period were quite conservative: Kalman filter, fuzzy theory, CNN. The terms of the more recent period (the first column) appear more interesting: e.g., attack detection and non-intrusive load monitoring. As energy systems grow more complex, the role of these factors may increase accordingly, and Energy Internet approaches will be more in demand.

The list of the 10 most common terms in the fifth cluster:

energy internet: 110; transmission line: 24; internet of things: 16; power quality: 16; voltage stability: 15; integrated demand response: 14; deep reinforcement learning: 13; edge computing: 13; energy router: 13; power flow calculation: 13.

The term "Energy Internet" dominates by a wide margin in this cluster. The terms that follow add more dimensions to its definition, for example: power quality and voltage stability. However, it is the sequence of terms that is of the greatest interest for the purposes of this study: integrated demand response, deep reinforcement learning, edge computing, which together define a compelling topic for

Table 5. Ten Terms of the Fifth Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year.

Max avg. pub. year terms	Min avg. pub. year terms
electricity retail market	electric heating
optimize operation	multi-microgrid
multiple time scales	real-time simulation
deep reinforcement learning	distributed optimization
renewable energy consumption	ems
photovoltaic power	voltage quality
extreme learning machine	reactive power
analytic hierarchy process (ahp)	energy management system
combined heat and power	cyber-attack
ice melting	cyber-physical system (cps)

research on complex energy systems. Table 5 lists the terms of the fifth cluster that appeared in newer and earlier publications.

The list of newer terms indicates the objects of research (electricity retail market and renewable energy consumption) along with a multi-level approach to solving currently relevant problems (multiple time scales, analytic hierarchy process (AHP), deep reinforcement learning). That only serves to clarify the topics listed above: integrated demand response, deep reinforcement learning, edge computing.

To explore the topic further, we provide a concise overview of several contributions that serve as specific instances of texts dealing with the topic.

For example, the authors of [3] argued that existing smart building management algorithms based on optimization suffered from the high cost of both building-specific modeling and on-demand computational resources. They proposed a reinforcement learning (RL) agent based on a surrogate building model derived automatically from building operation data. The agent learned the optimal management policy on the cloud infrastructure, and then this policy was extended to the edge devices for execution. With the proliferation of smart appliances (e.g., appliances with computing and data analysis capabilities) and high-performance computing devices (e.g., graphics processing units) in the households, one could expect a surge in residential energy consumption caused by computation. The integrated home energy management system (HEMS) aims to maximize the homeowner's expected total reward, defined as the reward from completing edge computing tasks less the cost of electricity consumption, the cost of computation offloading to the cloud, and the penalty of violating the demand side management (DSM) requirements. Therefore, it is important to schedule edge computing as well as conventional energy consumption in a smart way, especially when the demand for computation and thus for electricity occurs during the peak hours of electricity consumption. This issue was discussed in Ref. [4].

The existing cloud computing paradigm is reluctant to address such issues and face challenges like rapid response and local autonomy. To address the above, Ref. [5] considered a power control framework combining edge computing with reinforcement learning, which made full use of edge nodes to sense network state and control power equipment to achieve the goal of fast response and local autonomy. Additionally, the authors focused on the non-convergence problem of power flow analysis and combined deep reinforcement learning with multi-agent methods to make intelligent decisions. The model was defined in terms of the state, action, and reward tuple.

The demand for boosting productivity in manufacturing systems makes the industrial Internet of things (IIoT) an important research field which is an offshoot of the Internet of things (IoT). Communication between massive heterogeneous industrial devices and clouds will cause high latency and require wide network bandwidth. Ref. [6] made use of deep reinforcement learning (DRL) to solve the scheduling problem in edge computing to improve the quality of services provided to users of IIoT applications. Next, the authors proposed a hierarchical scheduling model that accounted properly for the heterogeneous architecture of central-edge computing. Double Deep Q-Network (DDQN) framework was proposed to make scheduling decisions for communication.

Power Internet of Things (PIoT) is a promising solution to meet the increasing electricity demand of modern cities, but real-time processing and analysis of huge data collected by the devices is challenging due to limited computing capability of devices and long distance from the cloud center. Ref. [7] discussed the edge computing-assisted PIoT where the computing tasks of the devices can be either processed locally by the devices or offloaded to edge servers. The authors pursued the aim of maximizing the long-term system utility which was defined as a weighted sum of reduction in latency and energy consumption. To that end they proposed a novel task offloading algorithm based on deep reinforcement learning, which jointly optimized task scheduling, transmitting power of the PIoT devices, and computing resource allocation of the edge servers.

Due to increasing complexity, uncertainty, and high-dimensional data in power systems, conventional techniques often hit a bottleneck when attempting to solve decision-making and control problems. Deep reinforcement learning (DRL) is one of the data-driven methods and is regarded as true artificial intelligence (AI). This field of research was instrumental in solving a wide range of complex sequential decision-making problems, including those in power systems. Ref. [8] contributed an overview of the topic.

Bibliometric analysis and clustering of terms based on their co-occurrence depend to a large extent on text preprocessing and slice formation, while helping to avoid exaggerated subjectivity in the selection of promising

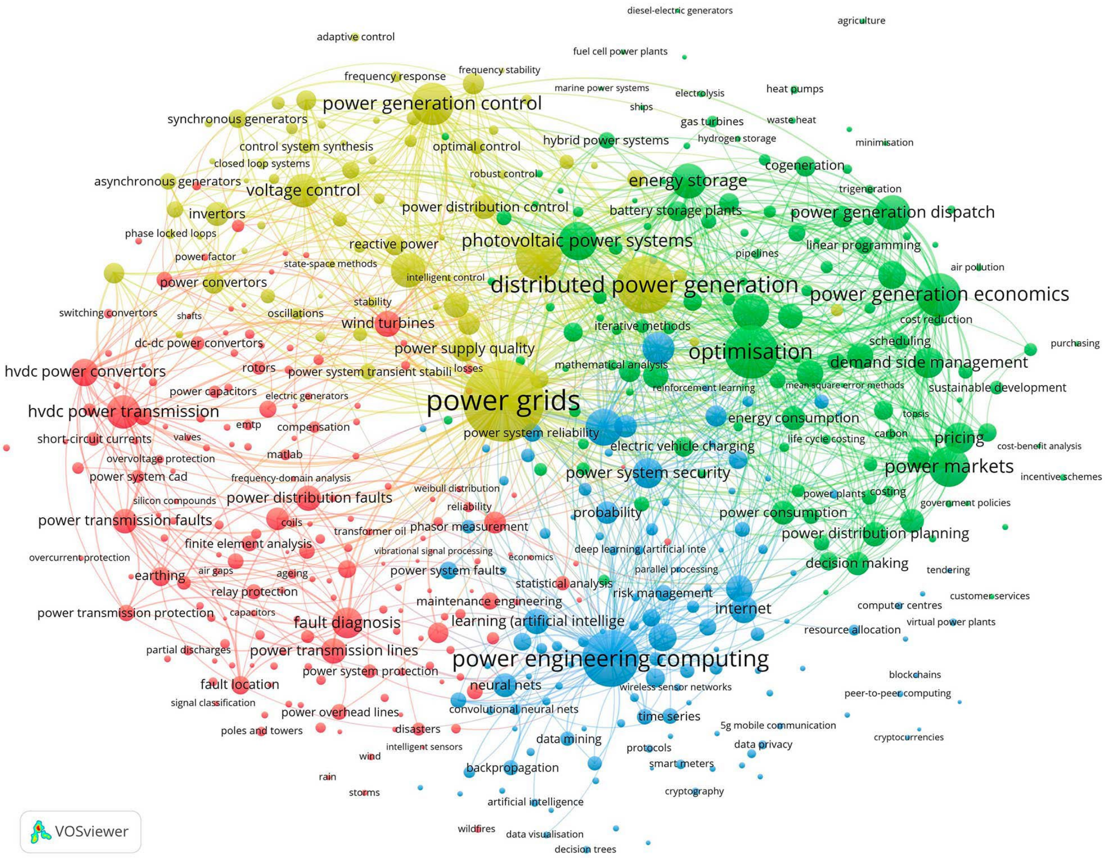

Fig. 3. INSPEC Controlled Terms co-occurrence map for 3 498 records.

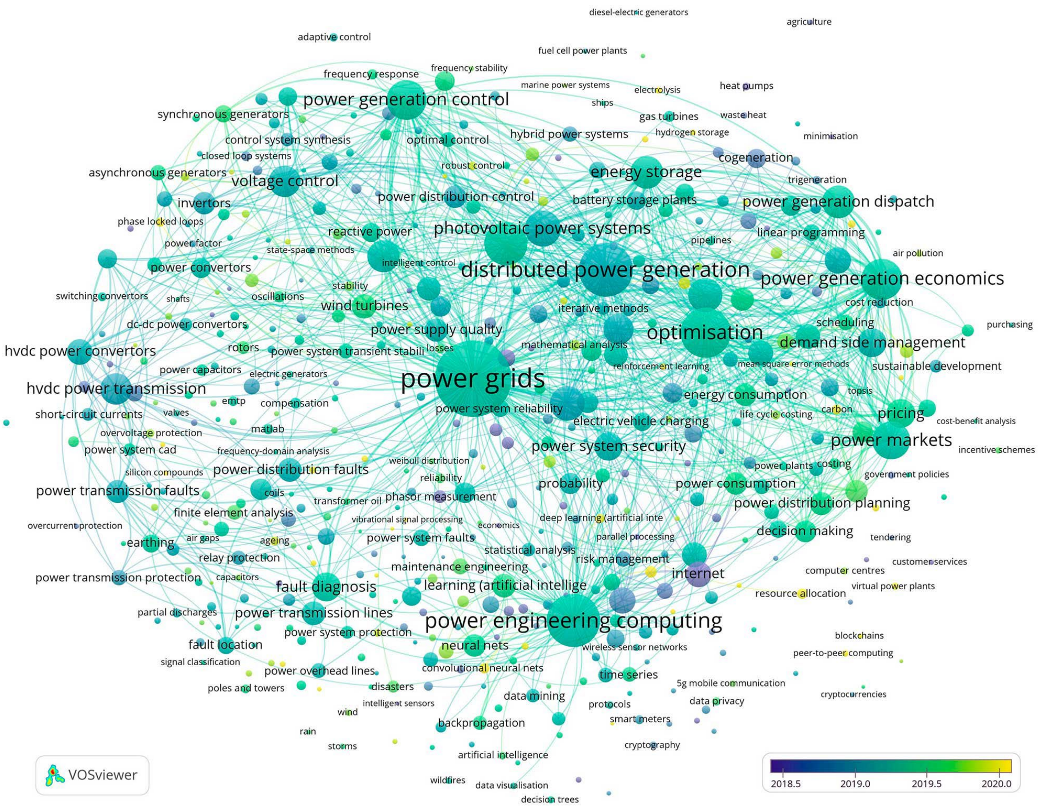

Fig. 4. Change over time of the INSPEC Controlled Terms co-occurrence network for 3 498 records.

focusing on tasks of immediate interest to them.

Authors of publications can also be thought of as experts, so their keywords, titles, and article abstracts reflect research priorities. The use of bibliometric data from their publications not only mitigates the possible bias of individual experts, but also allows us to highlight interesting problems that a particular expert may not have focused on. Conducting a broad survey of experts' opinions on a particular topic also reduces bias but is time-consuming and costly and may not be available to a small group of researchers.

B. *INSPEC Controlled Terms*

Keywords are assigned to articles from a controlled vocabulary of over 10 000 scientific terms created by INSPEC:

https://ieeexplore.ieee.org/Xplorehelp/searching-ieee-xplore/command-search

All 3 498 records contain 1,723 INSPEC Controlled Terms; 556 of them meet a threshold of 5 and 1 066 terms meet a threshold of 2.

As in the previous case, the 500 terms with the highest number of links were used to build the co-occurrence network. The reason for choosing a threshold of 2 terms is that it is better to use a larger sample to select the most connected terms.

The number of INSPEC Controlled Terms in our records was significantly lower than the Author Keywords: 1 723 versus 9 722. More than half of them occurred 2 or more times (1 060), while in the case of Author Keywords, 1 641 terms out of 9 722 meet this criterion. The large co-occurrence of INSPEC Controlled Terms and their limited diversity led to a small number of clusters (4), even if the value of the parameter of the minimum number of terms in the cluster was equal to one.

The rendering of the co-occurrence network is compact (see Fig. 3), and the change in term occurrence over time is minimal (see Fig. 4).

We can see that the colors of the key terms refer to the middle of the time range, which is significantly different from Fig. 2.

It should also be noted that the key term in the query to the IEEE Xplore abstract database, which is "Energy Internet", is absent from the INSPEC Controlled Terms.

Projecting the topic of the publication onto an established vocabulary leads, on the one hand, to well-defined clusters, but, on the other hand, it is impossible to identify newly introduced terms.

Thus, the use of INSPEC Controlled Terms to identify new topics of interest for more detailed consideration, as was done for Author Keywords, is not advisable. The INSPEC Controlled Terms are of interest as filters when refining queries to a reference database. This is the case, for example, when restricting the sample to issues related to "power engineering computing".

C. *INSPEC Non-Controlled Terms*

All 3 498 records include 3 168 INSPEC Non-Controlled Terms; 618 of these meet a threshold of 5 and 3 441 terms meet a threshold of 2.

By using the 500 terms with the highest number of links that meet a threshold of 2 to construct a network of terms co-occurrence, we ended up with 5 clusters by having at least 65 terms per cluster.

INSPEC Non-Controlled Terms are defined as "Additional keywords assigned to articles which describe the topics or subjects of a document. These terms are not part of the INSPEC controlled vocabulary and include new and emerging concepts." Therefore, it is reasonable to compare such terms with INSPEC Controlled Terms and identify those that do not occur in the controlled vocabulary. A comparison was made for the 500 terms from each list with the highest total number of links, i.e., those used to build the terms co-occurrence network.

There was an overlap of only 58 of the 500 terms compared. This means that these were significantly different samples.

Below is a list of 10 terms that appeared frequently in 500 INSPEC Non-Controlled Terms but did not appear in 500 INSPEC Controlled Terms, which was checked by direct search to eliminate variations in the spelling/wording of terms such as energy system or energy systems: energy internet – 96; integrated energy system – 62; distributed generation – 56; energy storage system – 45; control strategy – 38; smart grid – 38; active distribution network – 33; demand response – 32; electricity market – 26; microgrid – 23.

These terms are different from recently introduced terms. The above was verified by searching for these terms in the titles and abstracts for each year. The results are shown in Table 6.

Note: The notation used in the headings in the table was as follows: 17–21 – years 2017 to 2021, N – the number of times the term occurred in the titles and abstracts of a given year, R – the number of records in which the term occurred.

Table 6: Term Frequency by Year in the Texts of Titles and Abstracts

Term	17N	17R	18N	18R	19N	19R	20N	20R	21N	21R
energy internet	178	78	138	55	48	23	70	31	49	20
integrated energy system	44	22	73	34	33	12	76	29	129	52
distributed generation	58	35	53	31	19	12	51	25	64	30
energy storage system	54	31	48	29	44	25	76	35	72	41
control strategy	121	67	130	66	72	41	85	50	141	69
smart grid	47	26	42	29	16	10	43	21	23	15
active distribution network	27	13	36	17	5	2	38	15	30	17
demand response	49	24	55	23	34	15	56	28	115	43
electricity market	13	12	23	14	24	12	34	18	49	23
microgrid	177	44	188	50	84	27	128	36	170	50

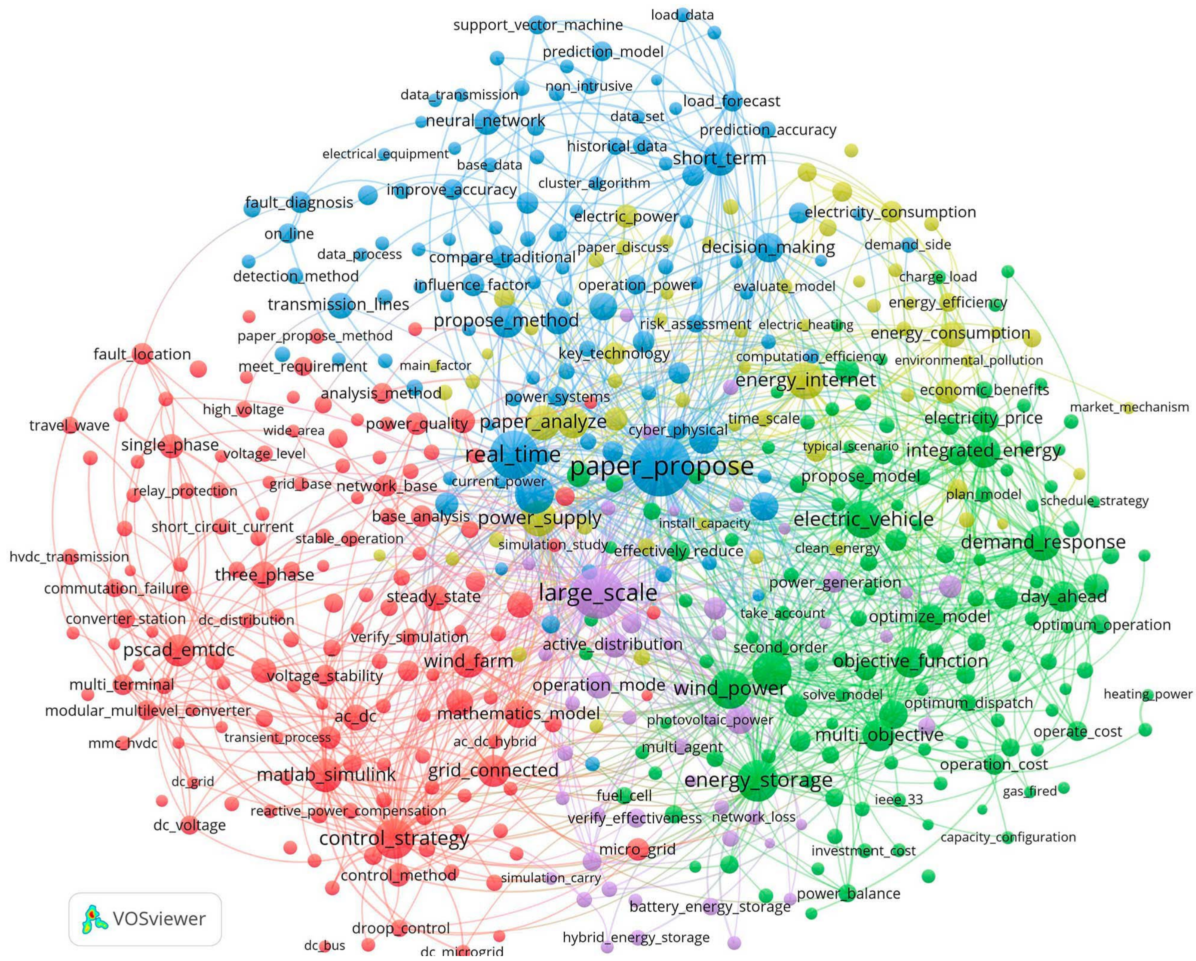

Fig. 5. Co-occurrence map of N-gram Terms from Title and Abstract fields for 3 498 records.

Table 6 shows that these terms appear in conference publication titles and abstracts throughout the years. Therefore, INSPEC Non-Controlled Terms should not be used as those indicating emerging topics.

The terms covered by "INSPEC Controlled Terms" and "INSPEC Non-Controlled Terms" are very different from the words found in titles and abstracts, they rather reflect the categories to which the system assigns a particular entry in IEEE Xplore. Therefore, to identify promising targets, it is advisable to identify key terms and analyze their co-occurrence in titles and abstracts of conference proceedings, as was done for Author Keywords.

The simplest way to find key terms in texts is to identify n-grams. This approach requires text preprocessing of titles and abstracts. In this particular case, the text was made lowercase, then the stop words were removed, followed by Krovetz stemming.

D. *N-grams as Key Terms (N-gram Terms)*

Titles and abstracts of 3 498 records produced 16 754 N-gram Terms of which 2 261 occurred 5 or more times.

By default, the 500 N-gram Terms were grouped into 6 clusters (with only 6 terms in cluster 6); including at least 10 terms in a single cluster resulted in 5 clusters. These five clusters are shown in Fig. 5.

Just like in the case of Author Keywords, the tables were constructed for each cluster. The tables contain 10 N-gram Terms with the highest average publication time and the minimum average publication time. The results for the first cluster are given in Table 7.

The data obtained for the N-gram Terms were significantly different from those for Author Keywords: the former were more specialized, while the Author Keywords were more general in nature.

In order to identify possible topics covered by this cluster, it makes sense to give examples of published research containing the terms listed in the first column of the table.

Ref. [9] reported a calculation model applicable to multilayer feedforward networks in which weighted summation with positive and negative weights was performed separately in each layer, and the summation results were then fed to the next layers without the subtraction operation. Results of simulations indicated that the energy efficiency for calculating weighted sums was 290~TOPS/W, which was more than an order of magnitude higher than in modern digital AI processors, even though the minimum interconnect width used in the PoC chip was several times larger than in such digital processors.

Table 7. Ten Terms of the First Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
low_voltage_distribution	operation_control
transient_overvoltage	micro_grid
calculation_model	control_mode
circuit_breaker	bus_voltage
reliability_power_supply	theoretical_basis
voltage_direct_current	droop_control
optimum_control	output_power
wind_turbines	fault_conditions
verify_simulation	wide_area
doubly_fed_induction_generator	hvdc_transmission

Ref. [10] proposed a time-domain method to calculate the fault response in multi-terminal DC (MTdc) grids and evaluate the performance of hybrid DC breakers. Three parameters of the hybrid DC circuit breaker (i.e., current limiting reactor, arrester rated voltage, and time delay) were selected so as to be optimal with respect to maximum overcurrent, maximum overvoltage, fault clearance time, and energy absorption in arresters. The selection was based on analytical results and was achieved through multiobjective optimization. The proposed technique was based on traveling waves. The technique contributed the following: 1) a sound representation of fault performance by considering all created traveling waves; 2) a new approach to estimate the reflection coefficients; and 3) an approximation of the worst-case fault location.

A proper definition of microgrids (MG) is that of distribution systems with integrated distributed energy resources, i.e., photovoltaic (PV) and wind power generation systems. Ref. [11] reported an efficient system for controlling the maximum power of a microgrid fed by PV modules and a wind turbine. The boost chopper duty cycle was adjusted to set the PV panel operating point to a maximum power point for the proposed PV maximum power point tracking (MPPT). In the case of the proposed wind turbine, a slope angle controller was designed to force the wind turbine to achieve optimum operation at low to medium wind speeds.

As can be seen from the above summaries of the three articles, they deal with very specific tasks. Therefore, the selected n-gram terms should mainly be used by subject matter experts as hints for making queries to abstract databases in line with their professional interests.

Next, the same procedure was applied to the terms of the second cluster with the results presented in Table 8.

The table shows that newer and older terms are related to economic issues. Older terms are less specific.

The following are examples of articles where the terms from the first column of the table occurred.

The articles were selected as examples from various sources; it is the topic, not the source, that is important.

Ref. [12] addressed the issue of the production of electricity by renewable energy microgrids (REM), which is a prerequisite for achieving one of the Sustainable Development Goals (SDG 7 – Affordable and Clean Energy). The microgrid configuration proposed in the

Table 8. Ten Terms of the Second Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
total_cost	energy_supply
economic_operation	power_demand
energy_conversion	combine_cooling
capacity_configuration	natural_gas
particle_swarm_optimize_algorithm	energy_demand
low_carbon	charge_load
wind_power_consumption	optimum_solution
optimum_configuration	security_constrained
life_cycle_cost	energy_flow
key_issue	energy_hub

Table 9. Ten Terms of the Third Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
model_power	power_load
data_driven	method_propose
safe_operation_power	monte_carlo_method
convolution_neural_network	k_means
weather_conditions	data_transmission
load_data	smart_grid
current_power	communication_technology
prediction_accuracy	base_data
influence_factor	power_fluctuate
electrical_equipment	computation_efficiency

paper minimized CO_2 emissions (by 92.3%) and fuel consumption (by 92.4%) compared to the case of using a fossil-fueled diesel generator. Optimal REM sizing leads to certain nonconvexities and nonlinearities, which rules out the use of deterministic optimization search methods.

Ref. [13] reported a hybrid wind-solar microgrid (MG) with biomass and energy storage to serve the loads demanded by buildings in the intended region and provide economic dispatch as well as power trading by supplying/receiving energy to/from the utility grid. A Hybrid Grey Wolf with Cuckoo Search Optimization (GWCSO) was used to achieve the optimal size of the proposed MG connected to the grid. The control operations plan included storage batteries to compensate for energy shortages if priority resources (wind turbine and solar PV) failed to meet the demand. Renewable energy systems, especially in countries with limited fossil fuel resources, are promising and environmentally sustainable sources of electricity generation.

Table 9, just like the previous table, lists the terms that make the third cluster.

Overall, this n-grams cluster refers to data processing methods in energy systems applications: model_power, convolution_neural_network, prediction_accuracy, influence_factor, monte_carlo_method, k_means and computation_efficiency.

The following are examples of articles that contain the terms listed in the table.

Demand forecasting in power systems is the most important task to be addressed by power engineering. It is important to build reliable and efficient forecasting models to ensure accurate load forecasting. Ref. [14] used the following three methods for short-term load forecasting: deep neural network (DNN), multilayer perceptron-based artificial neural network (ANN), and decision tree-based prediction (DR). The results indicated that the DNN model outperformed the other models and was statistically different from them.

The review article [15] identified and articulated a research problem related to load forecasting. Accurate modeling and sophisticated short-term load forecasting (STLF) analysis are becoming increasingly important for microgrids (MGs). For a quick overview of the results, they are presented in the form of tables.

Next, we repeated the same procedure for the terms in the fourth cluster and presented the results in Table 10.

It follows from this table that neither energy_internet nor energy_saving are new terms in this cluster. We also note that Carbon_emissions, spot_market, analyze_impact are the terms that receive increasingly more attention in publications.

Table 10. Ten Terms of the Fourth Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
carbon_emissions	energy_saving
spot_market	business_model
analyze_impact	electric_power
install_capacity	energy_management
comprehensive_evaluate	propose_base
renewable_energy_consumption	evaluate_method
power_source	environmental_pollution
main_factor	development_energy_internet
high_quality	interconnecte_power
quantitative_evaluate	energy_internet

Below are examples of the articles typical of the topic: carbon_emissions, spot_market, analyze_impact and electric_power, energy_management.

The carbon trading market is an important policy tool that contributes to China's carbon neutrality goals. Ref. [16] focused on identifying the relationship between the carbon market and other related markets. The results demonstrated that the information spillover effect between China's pilot carbon markets, the energy market, and the stock market was relatively low. If investors and policymakers treat each market from a systems perspective, they will have a more accurate overall understanding of the markets and their interconnections.

To achieve carbon neutrality by 2050, Japan should accelerate the reduction of its dependence on fossil fuels, especially in energy-intensive sectors. One solution is to implement a carbon pricing system that converts emissions from fossil fuels into production and consumption costs. Ref. [17] examined the correlation between the price in the wholesale electricity spot market and the cost of carbon in nine regions of Japan through the carbon cost transfer ratio.

Repeating the same procedure for the terms of the fifth cluster, we get the results shown in Table 11.

In this cluster, the total number of terms was less (50) than in the previous ones (147 terms in the first one), so there appears to be more consistency between the two columns. However, most of the new terms were related to energy storage: pump_storage, battery_energy_storage, energy_storage_system. Accordingly, the following is examples of publications returned by these terms:

The electric power industry is undergoing a paradigm shift toward a carbon-free smart system, aided by growing energy demand, deterioration of long-lived physical assets, and global environmental concerns. Energy storage systems (ESS) can help maximize these opportunities and mitigate potential problems. Ref. [18] investigated the ESSs installed on end user's premises and the corresponding technologies, the various billing and pricing policies, and their potential from the perspective of system operators and end users.

Table 11. Ten Terms of the Fifth Cluster with the Highest Avg. Pub. Value Year and Minimum Avg. Pub. Year

Max avg. pub. year terms	Min avg. pub. year terms
frequency_modulation	network_topology
pump_storage	solar_energy
peak_shaving	distribute_energy
voltage_deviation	distribute_generator
frequency_regulation	strategy_base
virtual_power_plant	multi_agent
grid_connection	simulation_carry
distribute_photovoltaic	power_output
battery_energy_storage	renewable_energy_resources
energy_storage_system	distribute_power_supply

The Cloud Energy Storage System (CES) is a shared distributed energy storage resource. The random uncontrolled charging and discharging of large-scale distributed energy storage has a large impact on the energy system. Ref. [19] focused on two objectives: to present detailed plans for designing an ordered managed CES system in a real-life power system and to analyze the load curves of five types of distributed energy storage systems. To that end the authors relied on Monte Carlo simulation (MCS) to manage and operate the CES system.

Figure 6 shows the overall change in the occurrence of terms over time.

Comparison of this figure with Figure 4 indicates that the terms represented as n-grams extracted from titles and abstracts underwent a more notable change over time than INSPEC Controlled Terms. Consequently, they are more appropriate for identifying emerging topics.

IV. Conclusion

1. Bibliometric analysis of research articles to identify current research issues is often used as part of a systematic review. Such a review requires one to make a reasonable selection of several dozen articles from the thousands published during the period under review. Based on the above analysis, the following steps are proposed to select publications, the full texts of which will be used to answer to the questions posed in the systematic review (our guidelines apply to the IEEE Xplore platform):

A. Use INSPEC Controlled Terms for coarse filtering of publications suitable for review.

B. Next, narrow down the resulting sample with Author Keywords serving as an expert opinion on the assignment of the article to the investigated topic. Author words are more specific than INSPEC Controlled Terms, they are less numerous, and they change more often over time (which is important for assessing trends).

C. As the third step, identify frequently occurring terms in titles and abstracts of publications (e.g., by compiling a list of n-grams). This is advisable as it allows experts in the subject matter who are compiling a systematic literature review to select those terms that will help them find the

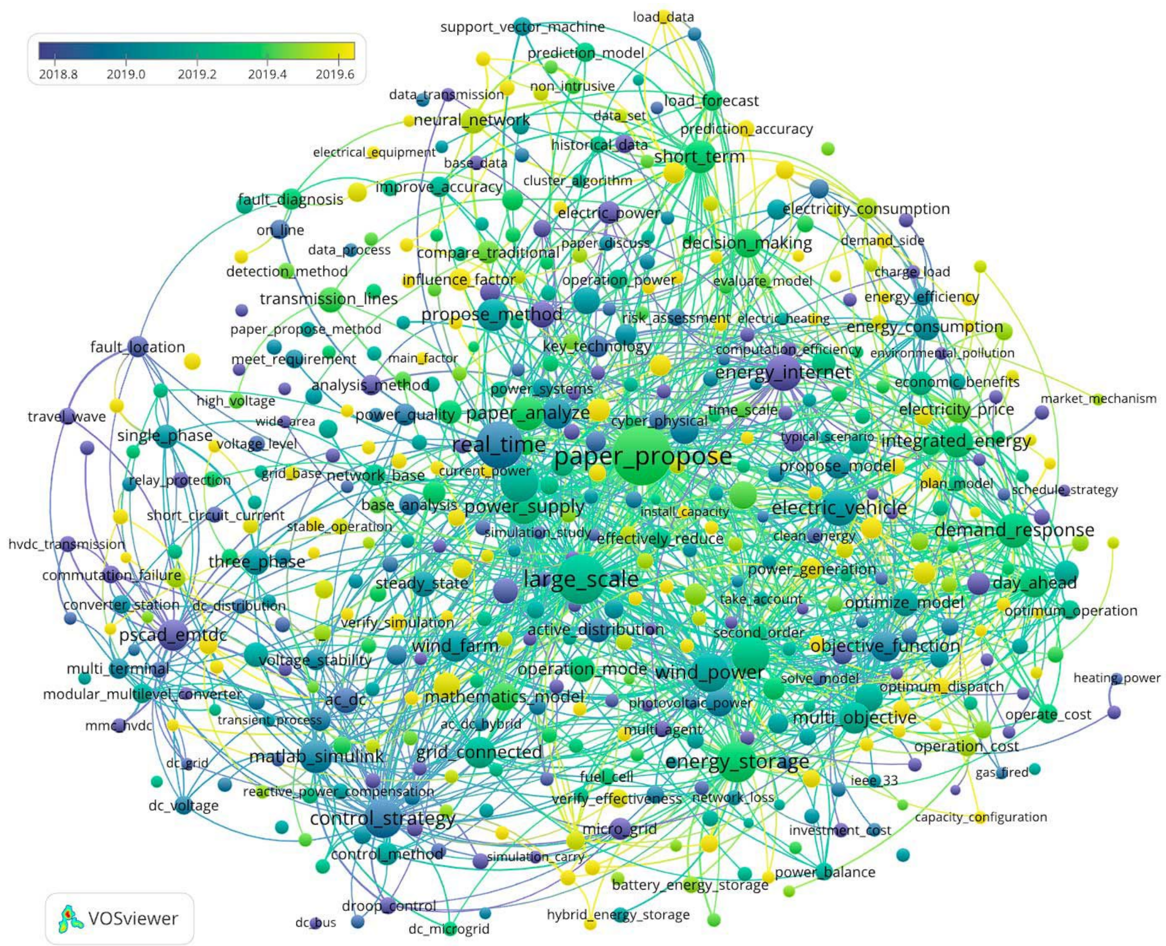

Fig. 6. Changes over time in the co-occurrence network of n-grams derived from Title and Abstract fields for 3 498 records.

answers to the questions posed in the review in the full texts of publications.

2. Based on the above analysis, we claim that the topic "A comprehensive demand-side power market based on an integrated energy system including microgrids, using the virtual power plant concept and optimization techniques that rely on deep reinforcement learning and edge computing" proves a topical issue that warrants further, more in-depth research.

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Comparative Analysis of Optimal PMU Placement Methods for State Estimation and Stability Margin Monitoring of Azerbaijans Power System

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Abstract **— To solve the problem of optimal placement of phasor measurement units (PMUs), we compare a method of integer linear programming and a method based on estimating the rate of change in operating parameters under heavy load conditions and disturbances. The former method solves the problem of optimal PMU placement in Azerbaijan's power system with respect to the criterion of full observability. The latter one investigates the rate of change in relative angles of synchronous generators under major disturbances and the rate of change in voltage and its phase in essential cutsets under increased load. The highest rates of change in operating parameters reveal weak nodes where PMUs should be installed.**

Index Terms**: phasor measurement unit, integer linear programming, load conditions, optimal placement, electric power system control.**

Abbreviations

CHPP	–	combined heat and power plant
EMS	–	energy management system
EU	–	European Union
ILP	–	integer linear programming
OHL	–	overhead lines
PDC	–	phasor data concentrator
PMU	–	phasor measurement unit
PP	–	power plant
SCADA	–	supervisory control and data acquisition
TPP	–	thermal power plant
UES	–	unified energy system
WACS	–	wide-area control system
WAMS	–	wide-area monitoring system
WAPS	–	wide-area protection system

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I. Introduction

Combating climate change, reducing greenhouse gas emissions, and meeting commitments under the Paris Agreement pose large-scale challenges for the energy sector being the largest contributor to climate change.

Within the framework of fulfillment of commitments under the Paris Agreement Azerbaijan has undertaken obligations to reduce the share of CO2 by 35% by 2030, compared to 1990 levels, and bring the share of green power to 30% by installing 1 500 MW of renewable energy capacity.

The agreement signed between the governments of the Republic of Azerbaijan, Georgia, Romania, and Hungary on strategic partnership focusing on green energy expansion and transmission envisages the transfer of 4 GW of wind power from the Azerbaijan sector of the Caspian Sea to the European Union countries in the next five years.

The world's longest electric cable will connect Azerbaijan and Europe, laying a green energy bridge between the Caspian region and the EU.

The goal is to boost the transmission of clean energy from the Caspian Sea to EU countries to 25 GW by 2037. To this end, different transmission schemes are examined: with integration into the power system, without integration into the power system, and asynchronous integration into the power system of Azerbaijan. In all cases, the large volume of transmitted power over long distances places stringent requirements on the reliability, stability, and resilience of Azerbaijan's power system.

The high requirements for reliability and resilience of Azerbaijan's power system, which is the key entity in such interconnections as Azerbaijan–Georgia–Romania–Hungary, Azerbaijan–Turkey–Greece, and Russia–Azerbaijan–Iran, necessitate the intelligentization of the power system [1–3].

II. WAMS as an Innovative Information and Measurement System

A most important component of the concept of intelligent power systems is an innovative information and measurement system based on phasor (vector) technology of real-time measurement. One of such systems is wide-area monitoring system (WAMS). PMU is an integral part of its structure, along with WACS, WAPS, and PDC systems [4–6]. WAMS provides information about the power system state every 20 ms with the measurement accuracy of ± 0.1% for voltage, ± 0.2 deg for phase angle, ± 0.2% for current, ± 0.01 Hz for frequency, and ± 0.20 for the angle between branch current and node voltage.

The vector of measurements performed by the PMU is represented as:

$$Y = [U_i \; b_i \; I_{ij} \; \Psi_{ij}], \tag{1}$$

where U_i is voltage magnitude of the i-th node; b_i is voltage phase of the i-th node; I_{ij} is the current flowing from the i-th node to the j-th node; Ψ_{ij} is the phase shift between current and voltage.

The system SCADA/EMS has already been installed and put into operation in Azerbaijan's power system.

The huge functionality of the system SCADA/EMS notwithstanding, it is outperformed by WAMS in several indices, including synchronization of measurements, volume, speed, and accuracy of information transfer. Tasks such as oscillatory stability monitoring, disturbance detection, event logging, post-fault analysis, and other tasks that require millisecond-order synchronous phase measurements are difficult to accomplish by means of SCADA/EMS. Under these conditions, the best performance is achieved by combining the capabilities of both SCADA/EMS and WAMS.

As mentioned above, the system SCADA/EMS has already been put into operation in Azerbaijan's power system, hence the focus should be on the PMU placement [7, 8].

One of the main criteria for optimal placement of PMUs in the power system is the criterion of full observability of the power system, which means that the number and composition of measurements suffice to control the power system operation under all conditions (before/during/after the accident). Naturally, this criterion (the observability criterion) can be met if PMUs are installed at all nodes.

However, the high cost of PMUs themselves with their current and voltage channels, the need to link these channels to the data concentrators (PDCs) at the locations of the latter, etc. requires a preliminary study.

Full observability can be ensured by using the measurements of voltage at the nodes with PMU and currents coming from these nodes to calculate the voltage and current at adjacent nodes. In this case, accuracy is preserved.

In the context of power system state estimation, where the identification of the power system layout plays a crucial part, of great importance is the topological aspect of observability, which is based on a linear system of equations.

The problem of optimal PMU placement in Azerbaijan's power system is solved by integer linear programming (ILP), where the extreme value of a linear function of many variables is found subject to linear constraints that relate these variables. In this case, the integer constraint is imposed on the variables. The original function to be minimized is represented as:

$$\min \sum_{k=1}^{N} x_k , \quad \mathrm{Ax} \ge \mathrm{b}, \tag{2}$$

where: N – the number of nodes in the system; x – a binary solution vector; A – an integer matrix, the structure of which depends on the network layout; b – an integer vector. In (2), the elements of matrix A take the following values:

$$a_{ij} = \begin{cases} 1, & \text{if } i = j, \\ 1, & \text{if } i \text{ and } j \text{ are connected}, \\ 0, & \text{if } i \text{ and } j \text{ are not connected}, \end{cases}$$

$\mathrm{x} = |x_1, x_2, \ldots, x_N|^{\mathrm{T}}$, where

$$x_i = \begin{cases} 1, & \text{if a PMU is installed an node } i, \\ 0, & \text{if there is no PMU}, \end{cases}$$

$\mathrm{b} = \left|1,1,1,\ldots,1\right|^{T}_{1\times N}$.

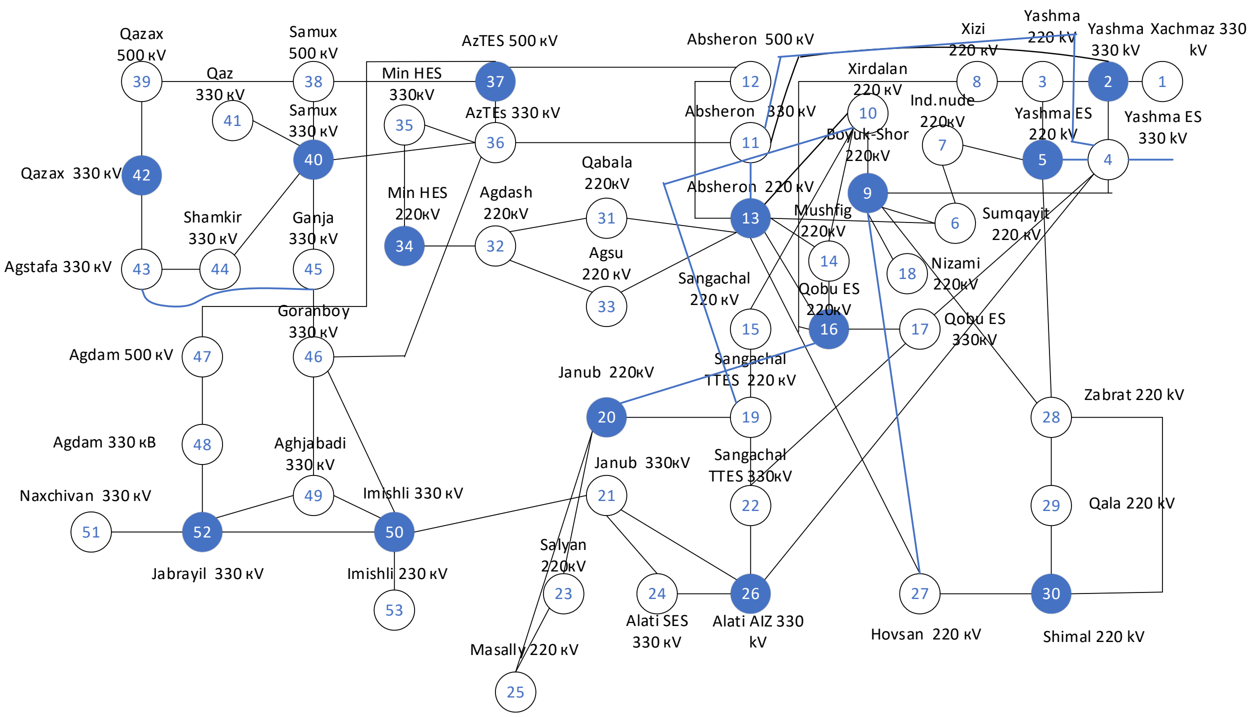

Fig. 1. Layout of the 500–330–220 kV network of Azerbaijan's power system (with PMUs indicated).

The ILP method is applied to a future possible layout of the 500–330–220 kV grid of Azerbaijan's power system, which has 53 nodes, including 24 nodes in the 500–330 kV grid and 29 nodes in the 220 kV grid (Fig. 1). Decomposition was made along the tie lines with the power system of Russia (330 kV OHL Khachmaz–Derbent), power system of Georgia (550 kV OHL Samukh–Gardabani, 330 kV OHL Agstafa–Gardabani), and power system of Iran (230 kV OHL Imishli–Parsabad, 330 kV OHL Imishli–Taqi–Dizaj).

The calculations implemented in the Matlab environment yielded the following PMU placement by node:

x = (0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 0 1 0 0 1 0 1 0 0 0 0 0 0 0 1 0 1).

These results indicate that full observability can be ensured by placing PMUs at 14 nodes (26% of the total number of nodes) of the power system, namely:

2 – 330 kV Yashma Substation (S),
5 – 220 kV Yashma Power Plant (PP),
9 – 220 kV Boyukshor S,
13 – 220 kV Absheron S,
16 – 220 kV Qobu PP,
20 – 220 kV Janub PP,
26 – 330 kV Alat Free Economic Zone,
30 – 220 kV Shimal PP,
34 – 220 kV Mingechevir HPP,
37 – 500 kV Azerbaijan TPP,
40 – 330 kV Samukh S,
42 – 330 kV Gazakh,
50 – 330 kV Imishli S,
52 – 330 kV Jabrayil S.

At the nodes adjacent to these nodes, observability is provided computationally by voltage and power flow measurements from the nodes where PMUs are installed. The analysis of the computational results shows the following. Each PMU has one voltage channel. The PMU at the 220 kV Absheron substation (node 13) has the highest number of current channels (9 channels). The node is essentially a boundary node for two decomposition subsystems: 500–330 kV (transmitting part) and 220 kV (receiving part) of Azerbaijan's power system.

A PMU with 5 current channels is installed at the 330 kV Imishli substation (node 50), which is the boundary node for the interconnection with the power system of Iran from the side of Azerbaijan's power system.

In addition, 3 PMUs are installed with 5 current channels, 6 PMUs with 4 current channels, 1 PMU with 3 current channels, and 2 PMUs with 2 current channels.

If the cost per channel is 1 notional unit, then the PMU cost would be 60 notional units.

Observability at the nodes of intersystem tie lines with the power system of Georgia (nodes 39, 42 and 43) and the power system of Russia (node 1) is provided by calculation (either for branches on the PMU side at the adjacent nodes of Azerbaijan's power system or the corresponding neighboring power systems).

Measurements of voltage phases at the ends of lines of the key cutsets of the transmission part (e.g., 37-12, 36-11, 34-13, 50-21) enables real-time monitoring of transfer capability and steady-state stability margins.

The data from the PMUs installed at busbars of the 500 kV Azerbaijan TPP (node 37), 220 kV Janub plant (node 20), and 220 kV Shimal plant (node 30), as well as the data obtained by calculation at busbars of the 330 KV Azerbaijan TPP (node 36) and the 220 kV Sumgait plant (node 6) are merged with information from SCADA/EMS at the same nodes, which allows monitoring the dynamic processes under major disturbances.

III. PMU Placement at "Weak" Components of the Power System

In the previous section, the sites for PMU placement in the 500–330–220 kV grid of Azerbaijan's power system were determined based on topological rules ensuring full observability of the power system. To that end, the integer linear programming method was used. It was recommended to install PMU at 14 nodes (≤ 27%) for the 53-node scheme of the 500–330–220 kV network (76 branches). The dynamics of operating parameters at other nodes and adjacent branches is calculated based on the measurements performed by installed PMUs.

Another approach to addressing the placement problems can be based on the physical content of the processes occurring in the system during disturbances. It is based on such concepts as heterogeneity, sensitivity, sensing capability, and weakness of the components of the topological structure of the power system.

In what follows we focus on the last two concepts being the sensing capability and "weakness" of components, which may suffice to solve the above problem.

Sensors are power system components whose operating parameters change to a large extent with random changes in such power system components as generation units, the grid, loads.

Weak components of the power system are those whose parameter changes have the greatest impact on the power system response to disturbances [9–11].

The uncertainty of the power system structure, operating conditions, disturbances, and the nature of dynamic processes under disturbances has led to differences in approaches applied to identify weak spots in the power system.

One such approach is a technique based on comparing the rate of change in operating parameters U, P, and δ under heavy-load conditions or disturbances, where U is node voltage, P is active power (stations, power transmission lines), and δ is relative angle between generators. Below we present examples of the approach in use.

The scheme and operating conditions taken as a basis are characterized by the following parameters:

$$P_G = 4\,459 \text{ MW}, P_L = 4\,330 \text{ MW},$$

where P_G is generation power, P_L is load power,
power transfer to Iran's power system – 500 MW,
including from the UES of Russia – 300 MW,
from Azerbaijan's power system – 200 MW.

IV. Rate of Change in Relative Angles of Synchronous Generators Under Major Disturbances

The outage of the 2nd 500 kV Absheron overhead line during the power flow of 464 MW without auto-reclosing was taken as a disturbance.

To compare the intensity of the dynamics of change in the angles, Table 1 shows the rates of change in relative angles between the main synchronous generators of the power system in the first swing cycle after disturbances (here δ_0 is initial relative angle, t_0 is initial relative time). They were calculated using the equation

$$V_\delta = \frac{\delta_{max} - \delta_{min}}{360\left(t_{max} - t_{min}\right)},$$

where V_δ is rate of angle change in the first swing cycle, δ_{max} is maximum relative angle, δ_{min} is minimum relative angle, t_{max} is time corresponding to the maximum relative angle, t_{min} is time corresponding to the minimum relative angle.

According to the Table, the highest rate of change in relative angles occurred between the following synchronous generators:

Azerbaijan TPP, 500 kV – Baku CHPP
Azerbaijan TPP, 500 kV – Shimal TPP
Azerbaijan TPP, 500 kV – Sumgait TPP
Azerbaijan TPP, 330 kV – Baku CHPP
Azerbaijan TPP, 330 kV – Shimal TPP

Therefore, for the purposes of monitoring of mutual angles on voltage busbars of synchronous generators it is advisable to install PMUs at the 500 kV Azerbaijan TPP and 330 kV Azerbaijan TPP in the surplus capacity part,

Table 1. Rates of the Change in the First Swing Cycle After Disturbances

	No.	δ_0	δ_{max}	t_0	t_{max}	V_δ
Azerbaijan TPP, 330 kV – Shimal PP	152-170	19	36.1	1.1	1.68	0.081
Azerbaijan TPP, 500 kV – Shimal PP	157-170	18.48	40.63	1.1	1.64	0.114
Janub PP – Shimal PP	170-211	10	–0.20	1.1	1.8	0.042
Azerbaijan TPP, 330 kV – Janub PP, 110 kV	152-211	29	36.49	1.1	1.56	0.045
Azerbaijan TPP, 330 kV – Sumgait PP, 220 kV	152-181	28.2	41.39	1.1	1.58	0.076
Azerbaijan TPP, 500 kV – Sumgait PP, 220 kV	157-181	27.69	46.33	1.1	1.56	0.113
Azerbaijan TPP, 330 kV – Baku CHPP	152-43	21.98	41.31	1.1	1.62	0.103
Azerbaijan TPP, 500 kV – Baku CHPP	157-43	21.46	46.08	1.1	1.60	0.138
Janub PP, 110 kV – Sumgait PP, 220 kV	211-181	–0.8	4.93	1.1	1.60	0.116
Janub PP, 110 kV – Baku CHPP	211-43	–7.02	5.17	1.1	1.66	0.060
Shimal PP – Baku CHPP	170-43	2.98	6.44	1.1	1.46	0.027
Shimal PP – Sumgait PP, 220 kV	170-181	9.2	3.7	1.1	1.78	0.023

Table 2. Values of Power for the Cutset Lines, Voltage at The Ends of Lines, and Their Phases

	Original conditions				Feasible conditions				Limiting conditions			
	P, MW	U, kV		δ^0	P, MW	U, kV		δ^0	P, MW	U, kV		δ^0
		U_L	U_k			U_L	U_k			U_L	U_k	
500 kV OHL Azerbaijan TPP – Absheron	433	504	463.3	7.8	468.4	504	460.3	8.5	581	493.4	431.8	11.4
330 kV OHL Azerbaijan TPP – Absheron	193	335.45	305.9	7.6	219	335	304	8.7	300	326.7	284.3	13.3
330 kV OHL Goranboy–Imishli	206.9	330.38	314.5	5.9	229.5	329.3	313	–6.6	305.3	318.3	294.6	9.7
330 kV OHL Goranboy–Agjabedi	317.1	330.38	316.2	4.4	351.3	329.3	314.4	5	458.8	318.3	296.1	7.1
220 kV OHL Mingechevir HPP–Aghdash (1)	113.9	231.41	228.2	2.2	123.3	231	227	2.3	151.6	221.4	216.1	3.1
220 kV OHL Mingechevir HPP–Aghdash (2)	113.9	231.41	228.2	2.2	123.3	231	227	2.3	151.6	221.4	216.1	3.1

and at the main stations in the part with the capacity shortage (Shimal TPP, Sumgait PP, Baku CHPP).

V. Rate of Change in Voltage and Its Phase in Cutset 2 Under Heavy-Load Conditions

Under the same initial operating conditions, the process of increasing the load forcing power system to operate under heavy-load conditions is initiated and the dynamics of change in the operating conditions of (500–330 kV) line of cutset 2 is considered successively: initial (1 378 MW), feasible (1 515 MW = 0.8 $P_{\lim}$ – 43, $P_{\lim}$ is limit power) and limiting (1 948 MW) conditions. Table 2 (where U_L is line start voltage, U_k is line end voltage, δ_0 is initial voltage phase) shows the values of power along cutset lines, voltage at the ends of lines, and their phases under the considered operating conditions.

Tables 3 and 4 presents the values of the rates of change in voltage at the ends of the cutset lines and the phase difference at the ends of these lines during the stepwise transition from the initial to the limiting conditions during the process of load increase.

The rate of change in voltage V_U was calculated using the following equation:

$$V_U = \frac{\Delta U_i}{\Delta P_i} \frac{P_{mi}}{U_{Ni}},$$

Table 3. Rate of Change in Voltage at The Ends of the Lines of Cutset 2 Under Heavy-Load Conditions

Cutset line	P_{in}→P_{feas}	P_{feas}→P_{lim}
500 kV OHL Absheron 2	0.1	0.294
330 kV OHL Absheron 1	0.0654	0.221
330 kV OHL Goranboy–Imishli	0.053	0.229
330 kV OHL Goranboy–Aghdash	0.071	0.266
220 kV OHL Mingechevir HPP–Aghdash	0.089	0.226

Note: P_{in} is initial power, P_{feas} is permissible power.

Table 4. Rate of CHANGE in Voltage Phase Difference at the Ends of the Lines of Cutset 2 Under Heavy-Load Conditions

Cutset line	P_{in}→P_{feas}	P_{feas}→P_{lim}
500 kV OHL Absheron 2	0.198	0.26
330 kV OHL Absheron 1	0.221	0.296
330 kV OHL Goranboy-Imishli	0.167	0.217
330 kV OHL Goranboy-Aghdash	0.140	0.156
220 kV OHL Mingechevir HPP-Aghdash	0.0284	0.0738

Note: P_{feas} = 0.8 P_{lim}.

where ΔU_i, ΔP_i is voltage and power change at the end of the i-th power flow line; U_{Ni} is nominal voltage value; P_{mi} is value of power on the i-th line under the limiting conditions.

The rate of change in voltage phase difference at the ends of the lines V_δ is calculated using the following equation:

$$V_\delta = \frac{2\pi}{360}\frac{\Delta\delta_{ij}}{\Delta P_i}P_{mi},$$

where $\Delta\delta_{ij}$ is voltage phase difference at the ends of the considered line; ΔP_i is change in power on the i-th line under the limiting conditions, P_{mi} is power value on the i-th line under the limiting conditions.

Analysis of the data presented in the table attests to the following:

1. The rate of voltage drop increases as the limiting conditions are approached, it occurs to the greatest extent at the end of the 500 kV OHL Absheron 2, i.e., at the 500 kV Absheron substation.

2. The rate of increase in the voltage phase difference at the ends of the cutset lines rises as well, and it occurs most intensively along the 330 kV OHL Absheron 1.

These findings indicate that control of voltage and its phase under the minor disturbances along cutset 2 should be carried out at the 500 kV Absheron and 330 kV Absheron substations.

The results support the conclusions on the installation of PMUs in the power system, which were reached by applying the integer linear programming technique.

According to Fig. 1, phasor measurements at 500 kV Azerbaijan TPP are carried out by a PMU, and at 330 kV Azerbaijan TPP, 500 kV Absheron substation, and 330 kV Absheron substation, they are calculated based on measurements at opposite ends of adjacent branches.

This study provided the rationale for additional installation of PMUs at the plants of the network part that experiences the capacity shortage, i.e., the Sumgayit power plant and Baku CHPP.

VI. Conclusion

The sites for placement of PMUs in Azerbaijan's power system and their number obtained by integer linear programming were in strict compliance with the criterion of topological observability. However, their high cost, which is due to both their number and the number of current channels, requires adjustment of the obtained results to match operating conditions specific to the power system. The available tie lines used for transit flows and the presence of critical cutsets in Azerbaijan's power system drive the need for PMU placement at "weak" points, where measurement-based monitoring of the stability and voltage levels, damping properties, low-frequency oscillations, and others are necessary.

In addition to complying with the observability criterion, which factors in the specific features of operating conditions, the future layout of Azerbaijan's power system necessitates PMUs to be installed at the busbars of power plants in the deficient part of the power system.

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Feasibility Study and Design of Smart Low-Energy Building Electrical Installations (Case Study: Isfahan University, Virtual Faculty Building)

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Abstract **— Buildings, particularly office buildings, are major energy consumers and sources of CO_2 emissions, contributing to around one-third of global energy consumption. As a result, energy consumption optimization regulations and the deployment of renewable energy technology in the construction sector has the potential to significantly reduce energy consumption and carbon emissions. This paper describes a comprehensive study on the technical feasibility and design of the electrical equipment of the Isfahan University virtual faculty building project in accordance with Iran's standards and guidelines of low-energy buildings (mostly chapter 19 of the Iranian National Building Regulations). In this case study, relevant designs and calculations were presented in order to accomplish the low-energy construction goals for various portions of the project. The photovoltaic system on the roof provides a part of the building's energy, and the KNX protocol was used to operate the lighting management system, the cooling and heating systems, and to enable intelligent energy management. As a result, the consumption of the lighting system using high-efficiency LED panels is less than 11 W/m^2. In order to ensure safety requirements, the main bonding system and ground electrode were designed in accordance with the site characteristics and standard criteria. Low-loss transformers are utilized to power the facility, and a soft starter, a multi-speed control, and a start-up system are used in the utility room. To achieve a minimum power factor of 0.94, a capacitor bank equipped with detuned reactors is employed for reactive power compensation. This paper focuses on the details of this design and the resulting experiences.**

Index Terms**: low-energy building, renewable energy, optimization of energy consumption, smart building management system.**

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I. Introduction

Humans' increasing reliance on energy consumption has raised a number of problems and challenges in the context of sustainable and high-quality energy supply in many countries worldwide. To address these problems and challenges, an effective policy would be to optimize energy consumption patterns and utilize new energy supply technologies, such as renewable energy technology and building management systems. Optimizing energy consumption entails selecting patterns and adopting and implementing methods and policies for correct energy consumption that are desirable from the standpoint of the national economy and ensure the continuity of energy supply and the continuation of daily activities [1].

Renewable energy has experienced significant growth in recent decades. Previously seen as unattainable and unconventional, contemporary technologies are now being implemented in various industries as cost-effective solutions to address problems associated with outdated fuel systems and concerns over pollution and expenses. Buildings are the most numerous energy consumers. According to Iranian Students' News Agency (ISNA), around 40% of Iran's energy is consumed within the development sector [2]. Moreover, buildings account for 30% of the worldwide energy consumption and 27% of all hurtful emissions [3]. Therefore, optimizing energy consumption policies and expansion of renewable energy technology can have a critical impact on reduction in energy consumption and carbon emissions. In this regard, recent studies have investigated various aspects of low-energy buildings, or, in special cases, zero-energy ones.

A low-energy building is characterized by a design and particular specifications that empower it to supply living benchmarks and consolation with low energy consumption and carbon emissions [4]. Energy-efficient houses mostly have extraordinary designs. For example, their windows are planned to provide the foremost supply of daylight. These buildings can also benefit from intelligent lighting control, cooling and heating systems, as well as energy generation units such as solar air heating, solar water heating, active or passive solar heating to minimize the energy consumption of the building. All over the world, companies and non-profit organizations give guidelines and certifications to guarantee the energy supply to buildings and their processes and materials.

Low-energy buildings with high levels of insulation, effective heating and cooling systems, in combination with renewable energy sources decrease essentially energy demand [5]. Most of rural communities depend intensely on agriculture as their primary source of income. Energy efficiency requirements allow them to supply all benchmarks of living with negligible energy consumption and carbon emissions [6]. Urban zones are regular places with high population density. The buildings of these zones should incorporate features such as a proper thermal insulation, an appropriate control system for ventilation, a suitable size of heating and cooling systems, and the highly energy efficient doors and windows [7].

Since low-energy buildings are an appropriate solution to decrease carbon emissions, different studies have examined the impact of these buildings on a reduction in overall carbon emissions. In [8], the study examines a modern low-energy building within the Tibetan Plateau of China, which includes a sun powered heat pump system to supply the heating load in winter. The ventilation of the doors and windows of this building is designed to provide the least heating and cooling losses, so that the temperature inside the building is not less than 18°C without utilizing the heating system. The authors claim that this building spares approximately 6 724.3 kg of CO_2 emissions each year. In [9], an idea for planning a multi-energy framework for different low-carbon scenarios in low-energy buildings is introduced. This research considers a wide extent of generation units' technologies, such as gas microturbines and solid oxide fuel cells. The authors believe that the integration of hydrogen-based innovations and storage systems are effective arrangements to substantially cut down energy consumption and carbon emissions. As mentioned earlier, the integration of renewable energy technologies with buildings can foster the accomplishment of goals of low-energy buildings. One of the innovations that are most consistent with the building division is solar systems, including photovoltaic systems integrated with the building, solar air and water heating systems, and passive solar systems.

Similar studies have investigated the utilization of these systems in completely different buildings. The authors in [10] tried to discover the foremost beneficial way to build a photovoltaic system in a residential building in Oman, taking into consideration the local climate, the average monthly energy consumption, and the rates paid by the local electricity company. The average monthly energy consumption of this building is 550 kWh. One of the aspects considered in this study is the intensity of daylight that changes throughout the year. When the intensity of radiation is at its peak and the rate of power generation is at its most noteworthy, a photovoltaic system is considered as a reasonable choice to meet the building's energy needs. In addition, photovoltaic systems, primarily known as rooftop photovoltaic systems, have already been introduced in numerous parts of the world. For most office buildings, however, the rooftop photovoltaic system alone is not sufficient to achieve a low-energy building, since the energy required by offices is normally large and the roof space is restricted. The roof space is also used for other projects. Therefore, using photovoltaic systems integrated with the building structure can be a better option. In this case, any part of the building exposed to sunlight can become a photovoltaic electricity generator, and today there is almost no limit to what this technology can offer to architects and builders [11].

The paper [12] indicates that the use of transparent amorphous silicon solar cells in a building-integrated photovoltaic system reduced energy demand by 33.3% and the use of perovskite-based cells – by 24.5%. Many other advantages of building-integrated photovoltaic systems are listed in [13] and [14]. In addition to photovoltaic systems, many other photovoltaic systems discussed earlier can effortlessly be used in buildings to meet energy demand, especially for heating, ventilation, and air conditioning (HVAC), which account for nearly half of a building's total energy consumption [15]. For example, in [16], authors evaluate the performance of a novel passive air conditioning system using solar stacks, solar water heaters, and phase change materials as a complete air cooling and water heating system in Egypt. The results of this study show that the integration of solar cell stacks and the exchange of phase-change materials with cooling towers significantly decreases the temperature of the space during the day and night. In [17], investigation focuses on the energy consumption and power generation of a heat pump system with variable refrigerant flow and integrated photovoltaic technology in a five-story residential building in Cyprus. The power consumption of the variable refrigerant flow system ranges from 14 005 to 18 710 kWh/y, and the solar power system, with a total output of 13 kWh, can generate 23 200 to 23 650 kWh/y. In fact, photovoltaic systems supply 126 to 166 percent of the annual energy needs of variable refrigerant flow systems. In addition, the installation of the photovoltaic system will reduce CO_2 emissions by approximately 14 ton/y. In [18], the study is concerned with a solar source heat pump system in a low-energy residential building in Xingying, China. This system keeps the average temperature inside the building between 16.13 and 19.61°C. Moreover, the study claims that the solar air source heat pump system can reduce energy consumption by 55.38% compared to the conventional air source heat pump systems. Another part considered in this research is smart building management systems. Recent developments in the field of the Internet of Things (IoT) have led to the development of smart buildings. Management systems based on the IoT play an important role in optimizing smart building operations. The IoT, as a key technology in smart buildings, is essential for connecting embedded objects to sensors and actuators over the internet anytime and anywhere [19]. Depending on the IoT characteristics, an IoT-based smart building management system can deliver different types of information about operational processes, indoor climate, and user behavior to ensure energy sustainability and efficiency in buildings.

The main objective of [20] is to find key factors that provide decision-makers with an optimal set of adoption strategies for smart building management systems based on the IoT. The main results show that disaster prevention systems and energy management systems for office buildings; environmental monitoring and energy monitoring systems for smart factories are selected by the integrated decision-making model. In addition, the authors highlighted the interrelationship between laws, regulations, and ecosystem value chains for government action in this area. In general, modern building energy management systems use centralized control architectures that are incompatible with the topology of the building space. This system faces high configuration costs and difficulties in field setup, not to mention sharing information between systems. The study presented in [21] involves investigating a wireless sensor network framework and designing a network model for a smart building energy management system. Subsequently, a blockchain-based dynamic key management strategy for smart building energy management systems is proposed. Experimental results show that the proposed scheme reduces the time and space required for data storage and optimizes the control of energy management systems in smart buildings.

Commercial and administrative facilities such as universities typically have high energy consumption, as well as energy losses. This paper focuses on the feasibility study and design of the electrical installation of the virtual faculty project at the University of Isfahan. In this study, principles and criteria for the design of electrical systems in low-energy buildings are presented and proposed systems are introduced. The design of electrical installations in complex buildings requires the basic design information. These cases may include a set of design and implementation points that follow standard or well-known engineering principles. The system proposed in this paper includes a different set of smart building management systems; lighting, grounding, and equipotential bonding systems; lightning protection system, photovoltaic systems, low-voltage electrical equipment, transformers, uninterruptible power supplies, generators, capacitor banks, and more.

This study proposes an efficient lighting system evaluated with DIALux® software. Currently, DIALux® uses an algorithm that considers the light intensity distribution curve inside the window depending on the illuminance distribution in the sky and the daylight control system [22].

II. Investigation and Feasibility Studies

It is difficult to fully consider the contribution of sunlight when assessing the energy consumption of building lighting annually. There is a complicated overlap between daylight and electric light and increased planning challenges for their simultaneous use. Smart use of daylight can reduce the energy consumption for lighting by more than a third [23]. With the development of the new version of DIALux-evo, it is now possible to estimate the energy-saving potential of integrated daylight and electric lighting strategies in everyday lighting plans. Various studies are concerned with the room lighting optimization using the DIALux software [24, 25].

Therefore, in the current project, it is appropriate to estimate the available electric loads (especially the lighting load) in the first step. For this purpose, building demand information such as building maximum energy demand, demand factor, simultaneity factor, and load factor were gathered by reliable surveys and valid references. In chapter 4, various parts of the building's electrical system are calculated to meet demand while being designed to meet low energy targets. In [1], the authors review the mandatory criteria in the design of buildings; in the field of external surface; in heating, cooling, ventilation, and hot water supply systems; electrical installations, and lighting system to improve the energy performance of components and equipment and reduce the need for and consumption of building energy. In this regard, three levels of quality (energy class) of the building are defined by determining the energy efficiency [31]:

• The EC building complies with national building regulations.
• Low-energy buildings (EC+)
• Buildings with very low energy consumption (EC++)

Based on about 30 face-to-face meetings held before COVID-19 between the authors and the project investors, and coordination with the architecture and engineering team and employers, it was decided that the type of design would be a low-energy configuration or in line with EC+. Below are selected papers based on this energy category. Note that EC stands for Energy Compliant. According to [32], there are the following design methods:

• Prescriptive method
•Trade-off method
• Energy Need method
• Building Energy Performance method

The first three methods suggest that the design processes of building walls, mechanical and electrical systems are independent of each other. In contrast to these three methods, energy performance requires an integrated design that can be supported by dedicated software. This paper methodology is based on the Trade-off method.

2.1. Estimating the load (demand) of the building

Electrical demand is the power displayed by a wattmeter at the peak load (Fig. 1). To design the building's electrical installations, one must first make an accurate estimate of the load to enable various calculations based on it. As a result, an explanation relevant to demand calculation methods (load estimation) is mentioned in this section, and eventually, the project demand is estimated. The determination of simultaneity factors is one of the challenges that may emerge in relation to demand estimation of large projects.

2.2. Maximum demand

Maximum demand is known as the average power consumed in a given time period (typically 15 minutes) (Fig. 2). In practice, usually the goal for demand estimation is the maximum demand rather than the maximum power [33].

2.3. Demand factor

Due to the lack of simultaneous use of all electric loads, the demand factor is multiplied by the connected power to estimate real demand. The demand factor is plant-specific. The simultaneity factor has the same concept as the demand factor, but the former is used for several loads, whereas the latter is defined for only one load:

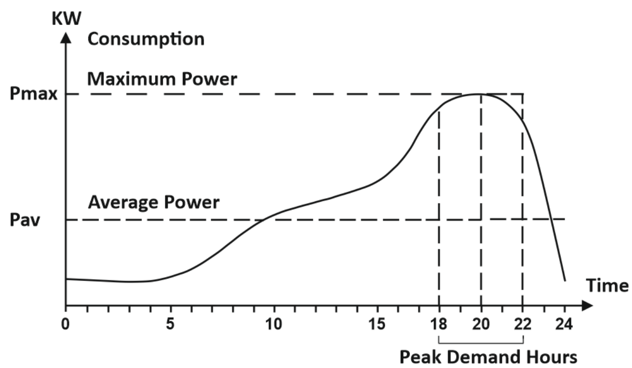

Fig. 1. Typical time variation curve of electric power.

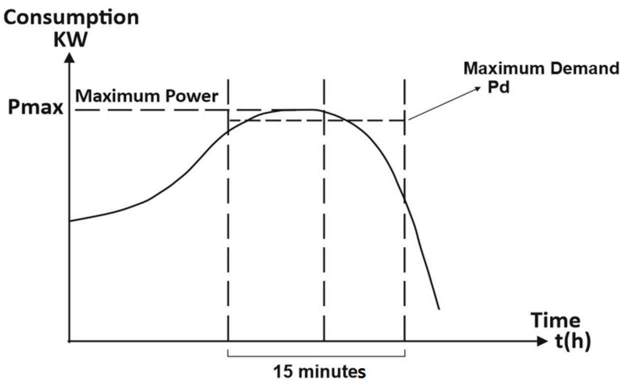

Fig. 2. Maximum demand and maximum power.

Total connected power per unit = Demand factor × Demand for one load;

Line Demand for similar loads = Power of one load × Simultaneity Factor × Number of similar loads.

For instance, if the demand of a utility room in winter and summer is 10.35 and 92.85 kW respectively, and the total installed power is 101.1 kW, then the demand factor is equal to:

For instance, if the demand of a utility room in winter and summer is 10.35 and 92.85 kW respectively, and the total installed power is 101.1 kW, then the demand factor is equal to:

$$g = \frac{92.58}{101.1} = 0.918.$$

2.4. Load factor

The load factor is defined as the average load (in kW) divided by the peak load (in kW) in a specified time period. The load factor closes to 1 indicates an optimal and economic use of the rated capacity of the equipment.

2.5. Simultaneity factor

To calculate the value of the simultaneity factor, the electrical designer requires detailed information on the project, loading conditions, future development plans, and other aspects. To calculate the maximum demand, the simultaneity factor can be taken from valid technical sources or similar projects. This study uses the simultaneity factor recommended in [34]. For different types of loads such as lighting, general socket outlets, single purpose electrical outlets, and other electrical loads, which are fed through electrical panels, suitable simultaneity factors should be applied to the total demand of all fed points (connected load) (Table 1).

Table 2 shows the simultaneity factors for switchboards based on different loads. Table 3 indicates the simultaneity factors for apartment complexes based on the number of consumers.

2.6. Total project demand

The project power demand is determined based on the power consumption of the lighting system, equipment, HVAC systems, and computers. They are presented in Table 4. Thus, the demand for this project is supposed to

Table 1. Simultaneity Factor for Final Circuits [34]

Circuit function		Diversity factor (k_s)
Lighting		1
Heating and air conditioning		1
Socket-outlets		0.1 to 0.2 (1)
Lifts and catering hoist (2)	For the most powerful motor	1
	For the second most powerful motor	0.75
	For all motors	0.60

(1)In certain cases, notably in industrial installations, this factor can be higher.

(2)The current to take into consideration is equal to the nominal current of the motor increased by a third of its starting current.

Table 2. Simultaneity Factor for Switchboards [34]

Type of load	Assumed loading factor
Distribution – 2 and 3 circuits	0.9
Distribution – 4 and 5 circuits	0.8
Distribution – 6 and 9 circuits	0.7
Distribution – 10 or more circuits	0.6
Electric actuator	0.2
Motors ≤ 100 KW	0.8
Motors > 100 KW	1.0

Table 3. Simultaneity Factor for Apartment [34]

Number of downstream consumers	Diversity Factor (k_s)
2 to 4	1
5 to 9	0.78
10 to 14	0.63
15 to 19	0.53
20 to 24	0.49
25 to 29	0.46
30 to 34	0.44
35 to 39	0.42
40 to 49	0.41
50 and more	0.38

Table 4. Power Demand of Each Section in the Project

Total area	5 892.78 m^2
Lighting system power (W) = area (m^2) × lighting power density (W/m^2)	65 kW
Equipment power in each section (W) = section area (m^2) × equipment power (W/m^2)	24 kW
HVAC power (gathered from HVAC designer report)	15 kW
Power of computers (W) = number of computers × typical power of a computer (W)	31 kW
Utility room power (gathered from utility room designer report)	200 kW
Total power demand	335 kW

be 350 kW for electrical facilities design (335 kW is rounded up to 350 kW).

2.7. Feasibility of the proposed plan

The project site is on University Street, on the west side of Isfahan (51° 39' 30"W, 32° 37' 16"N, 1599 AMSL). This building is built in 5 floors and has an area of about 7 000 m^2. Figure 3 depicts the geographical position and accessibility of the project site, whereas Fig. 4 shows the solar radiation situation in this location. Because of the policies of Iranian government and its International obligations, there is a strong desire to encourage the use of renewable energy sources. It is expected that the use of renewable energy sources will be the first priority in satisfying the project demand power. As Isfahan has an excellent potential with more than 300 sunny days per year, the use of solar power plants is preferable in this project.

As a result, the implementation of this project involves the use of grid-connected solar power plants and the investigation of the method of transferring their electricity. A grid-connected power plant was a candidate for a service period of 20 years, because according to the Iranian Ministry of Energy Policies, the project must supply at least 20% of its electricity consumption with renewable energies. It is important to emphasize that, according to [31], it is necessary to supply 30 kW of electricity by solar panels for this project to be classified as a low-energy building.

Given the wide range of products used in solar power plants, the project's initial costs will be around 25 000$. If the solar power plant's output is sold to the public grid, the financial projection and return on capital will take around 5 years. The remainder of the power plant's income will be profit, according to the distribution company's 20-year

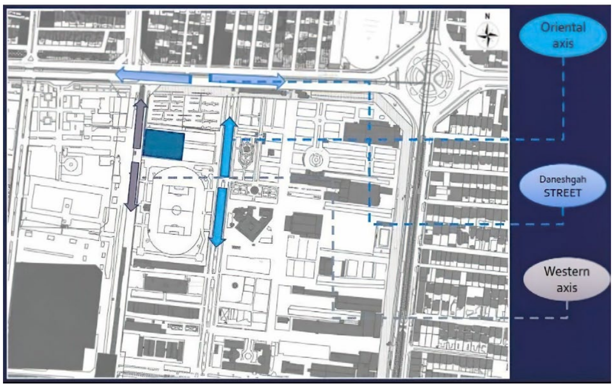

Fig. 3. Geographic location of the project.

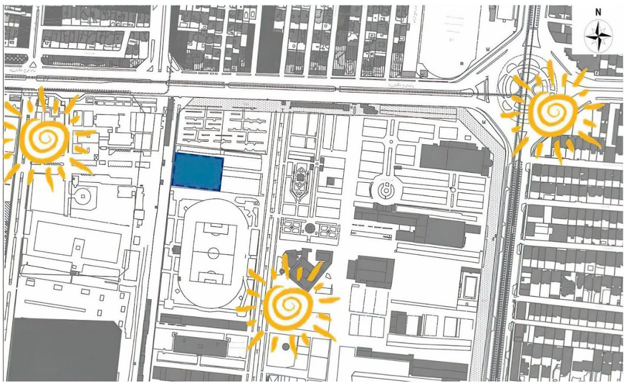

Fig. 4. The direction of sunlight in the project site.

deal.

The designs in the field of low voltage facilities and smart building control follow national building regulations [31]. There are two references to smart building management systems in this topic. The first is concerned with the control and monitoring of the cooling and heating system, and the second is for the lighting system. The building's cooling and heating can be supplied centrally or individually. Utility rooms and wall mounted gas boilers are considered as central systems, whereas heaters and coolers are considered as independent systems. All central and independent systems need appropriate control systems [31]. Each controlled space needs separate control systems to reduce the need for heating or cooling. Smart building control was also proposed for lighting system to implement a low-energy framework. The proposed solution was tested using the DIALux software. High-efficiency LED panels were used in classrooms and workplaces, which allows the goal of 11 W/m^2 for low-energy buildings to be achieved.

III. Designing The Electrical Installations of the Building

3.1. Solar system

The sun is the most abundant source of energy on the planet. The primary applications of solar energy are divided into two groups:

1. Solar thermal systems (direct conversion of solar energy into thermal energy);
2. Photovoltaic systems (direct conversion of solar energy into electrical energy).

Photovoltaic systems have various applications due to the benefits such as long life, ability to be installed and started up in inaccessible and hilly areas, ease of maintenance, absence of reliance on the grid in remote areas, ability to be connected to the grid, and others. According to Iranian Ministry of Energy Policies, educational institutions, government colleges, and their sub-units should be constructed providing 20% of their energy consumption with solar power plants [26].

3.1.1. Guaranteed purchase rate of solar electricity

The legal obligations of Iranian Ministry of Energy are fulfilled according to the principle of guaranteed purchase of electricity from photovoltaic power plants with an output of up to 100 kW (Table 5) (these rates refer to the study year). Undoubtedly, the new resolution proposes a price increase of 30% (1 Iranian riyal is approximately equal to 2×10^{-6} USD).

3.1.2. The requirements of renewable power plants

Designing a construction project needs to determine both its dedicated space and the route for the installation and commissioning of future renewable system circuits and associated infrastructure. The energy checklist must list separately the annual energy of the project and the annual energy that can be provided by renewable systems in the future (if expanded). The necessary studies and projections should be carried out for all the buildings to ensure that the amount of energy that can be supplied in the future does not fall below the following values [30]:

- 20 kWh/y/m^2 of the roof surface for one-floor buildings;
- 32 kWh/y/m^2 of the roof surface for buildings with more than one floor.

All relevant information must be recorded in the calculation and design notebook. In the cases where it is not possible to provide the minimum values due to special conditions caused by the construction of the building, such as shading from neighboring buildings, technical justifications must be provided, and the impossibility of using renewable energies must be clearly stated in the

Table 5. Guaranteed Electricity Purchase Rate

	Generators for electricity subscribers up to the limit of branching capacity		Base rate of guaranteed electricity purchase (Riyals per kWh)
1	Wind turbine with a capacity of one megawatt or less		5 700
2	Solar	With a capacity of 100 kW and less	7 000
		With a capacity of 20 kW and less	8 000

Table 6. The Minimum Annual Energy Provided by Renewable Systems (kWh/m^2) [31]

Energy class	The minimum amount of annual energy provided	
	One-floor	More than one floor
Energy Compliant (EC) building	14	22.4
Low-energy building (EC+)	20	32
Very low-energy building (EC++)	28.6	45.7

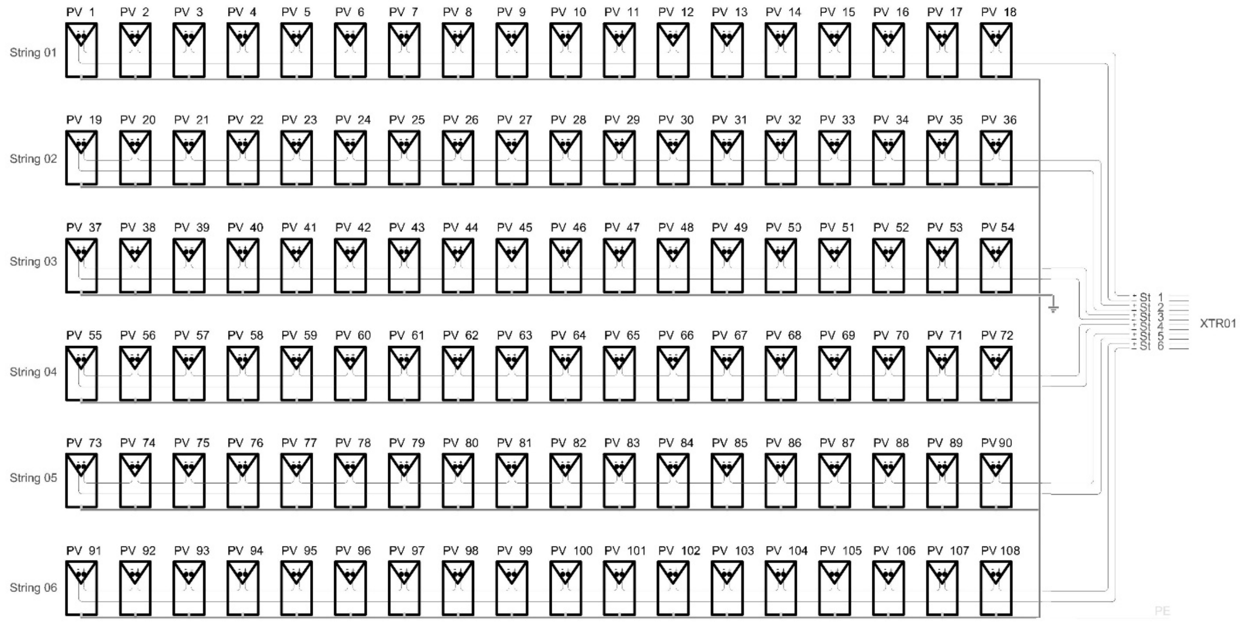

Fig. 5. The proposed power plant schismatic diagram.

building's technical documents. The suggestions for this project was to install panels on the building's roof and sidewalls, which was considered feasible given the sufficient available space on the roof.

Table 6 indicates the amount of renewable system use required for buildings according to [31], low-energy buildings, and extremely low-energy buildings. According to Table 7 and the figures given in [31], the required power of rooftop solar power plant is 30 kW approximately.

3.1.3. Photovoltaic system simulation

The PVSyst® software can be used to model a solar power plant necessary for the project. This software can compute the system's connection to the grid, disconnection from the grid (DC grid), and construction of solar pumps. The rated power of the system with 108 modules (6 parallel strings consisting of 18 series modules according to Fig. 5) at standard test conditions is equivalent to 40 kW, which meets the calculated demand of 30 kW. This power plant's annual production rate is 79.76 MWh, and its average performance coefficient for different months is assessed to be 85.34%. Figure 6 depicts a graph of power plant production and various system losses by month. Photovoltaic array losses (energy conversion losses) and system losses (inverter, wiring, etc.) are examples of these losses.

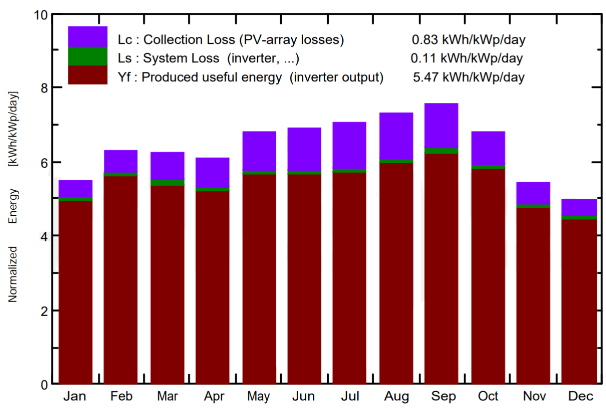

Fig. 6. Net production and losses of the proposed power plant in different months.

Shading is another critical issue in the design of solar power facilities. PVSyst® software divides shading into two categories: close and far shadings. Given the proximity of Mount Sofeh to the project, the distant shadows can be modelled in Meteonorm® software and then entered into PVSyst® software. As a result, the Meteonorm® software (Fig. 7) is employed in the designs and simulations of this project. According to the calculations, 30 kW solar power plant was sufficient, but according to the available space and the possibility of installation, calculations and placement for a 40 kW power plant were suggested. Figure 8 shows the schematic diagram of the proposed solar power plant switchboard.

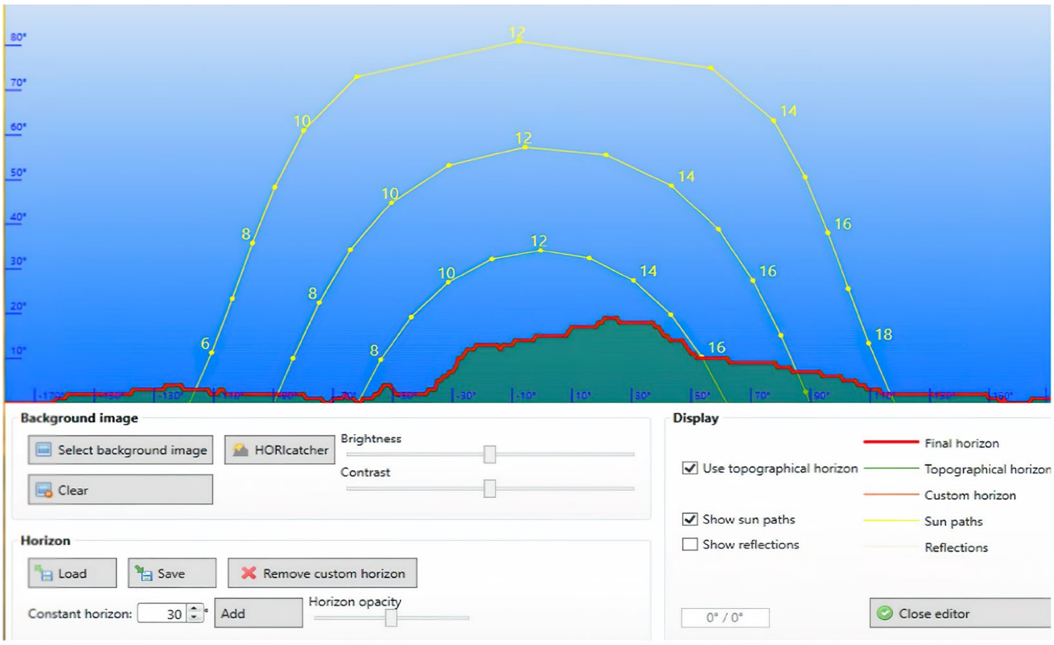

Fig. 7. Simulation of the far shadow (Sofeh Mountain) in Meteonorm® software.

3.2. Smart building management system

Given the high expenses of the smart building management system, the proposal for its re-implementation was restricted to lighting management and intelligent control of the cooling and heating systems, both of which are also implemented using the KNX protocol. KNX, formerly known as European Installation Bus (EIB), is a building control communication system that employs information technology to connect numerous pieces of equipment such as sensors, actuators, controllers, executive interfaces, and displays.

This technology is used in electrical installations to perform building automation scenarios and processes. The low-voltage facility of the building was designed and studied using Siemens Simaris® software (Fig. 9). The map

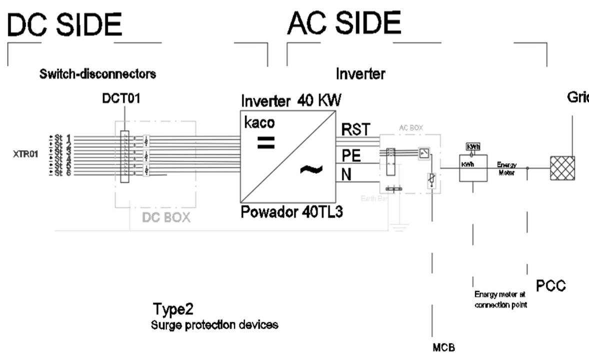

Fig. 8. Schematic diagram of the proposed solar power plant switchboard.

of the building's smart boards is also shown in Fig. 10 and 11.

3.3. Lighting management system

DIALux software was used to evaluate the proposed lighting system. Figure 12 shows the ground floor zoning map, while Table 7 depicts the zone calculations. Figure 13 presents the color index of the incorrect ground floor components. Figures 13 and 14 demonstrate a 3D depiction of the ground floor. LED panels with high lumens per Watt are utilized in classrooms and offices, and with this choice, the goal of 11 W/m^2 for low energy buildings can be achieved. We can also utilize Downlight LEDs depending on the type of use and places, particularly in hallways with fake ceilings. Gobo projectors are recommended to light the building's northern wall. It is possible to reflect the green building logo, the university logo, and others on the building, which, in addition to its beauty, highlights the structure's low energy use. To use natural light, the appropriate arrangements with the architectural designer should be made to enable (if possible) alterations to the architectural plan of phase 1 in order to reduce the need for lighting in public spaces during the day.

In [31], the daylight simulation method is based on the SDA index. This index is expressed as a percentage of the floor area in which the minimum intensity of the desired lighting is provided in 50% of the specified hours and it is equal to 75–85% for low-energy buildings.

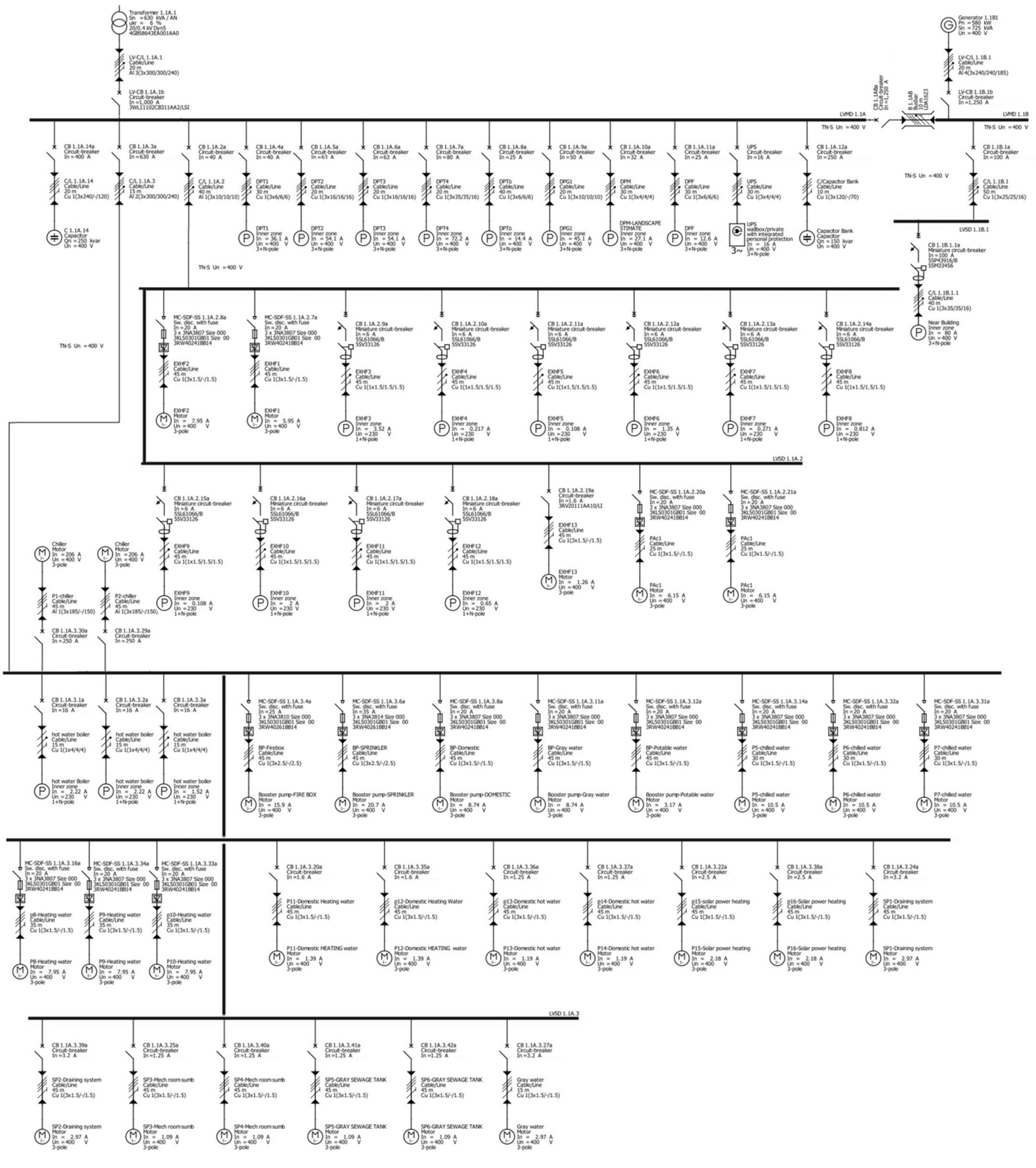

Fig. 9. Simulation of low-voltage system in Simaris software.

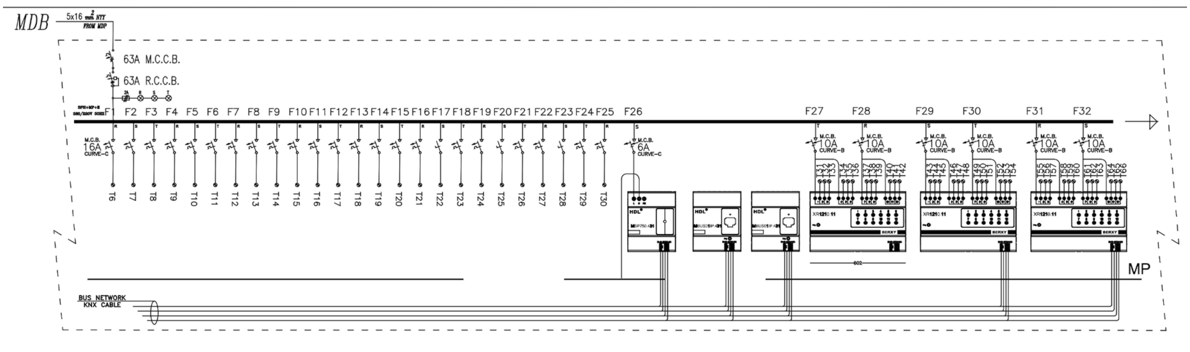

Fig.10. Single line diagram of the smart building boards.

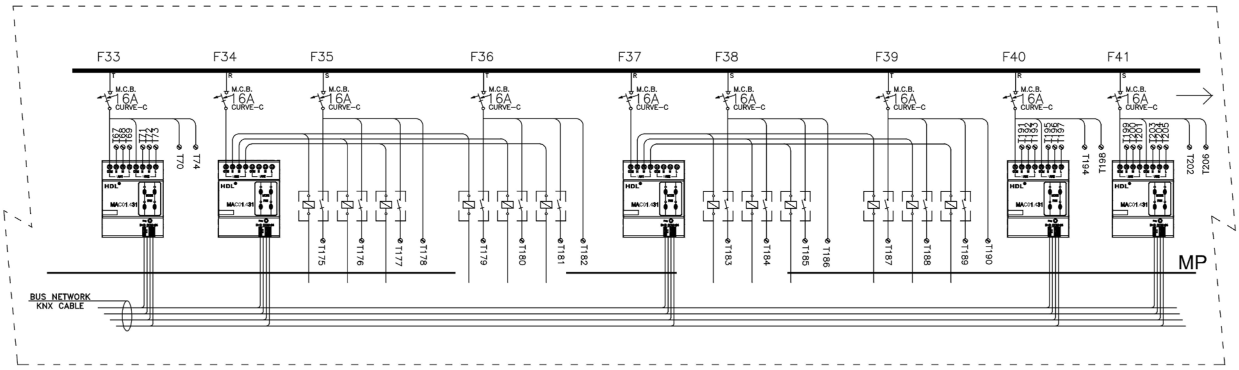

Fig. 11. Single line diagram of the smart building boards.

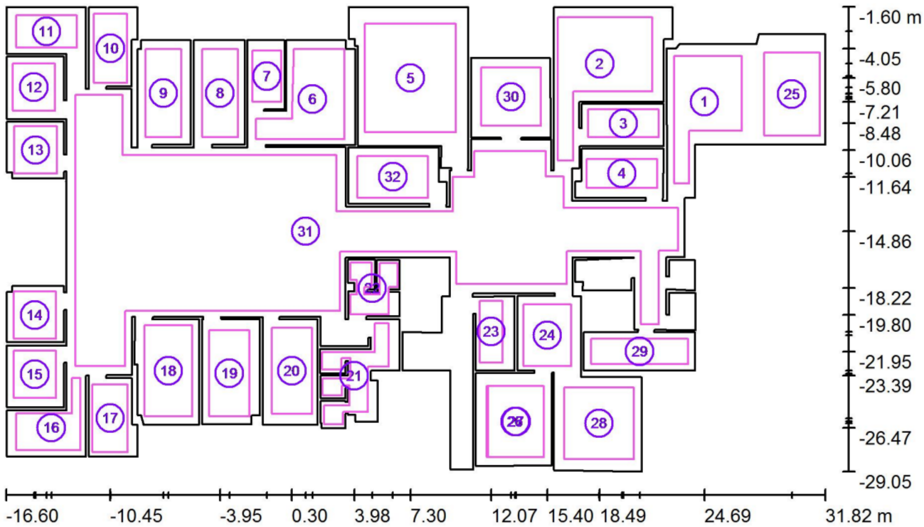

Fig.12. Ground floor zoning map.

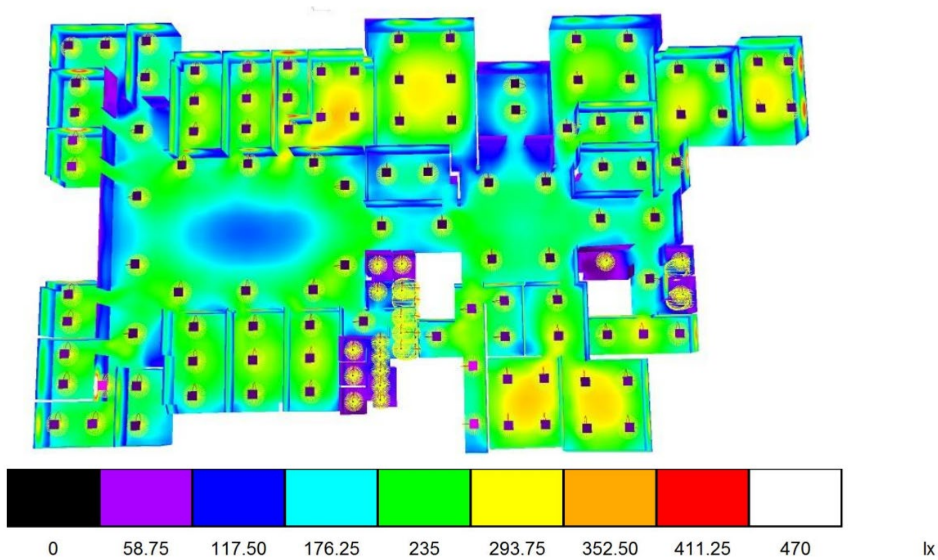

Fig. 13. Ground floor color index.

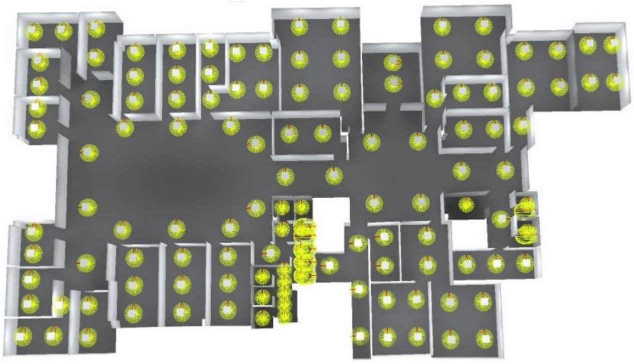

Fig. 14. 3D rendering of the ground floor lighting system arrangement.

3.4. Grounding and equipotential system

The ground system was designed according to [35] and [36], and the main structure was designed following [37]. The authors of [27] show how to calculate a shared ground system and connectivity. Because the project substation is located inside the building structure, it is not possible to separate the earth electrodes of low and medium voltage. As a result, a common ground electrode with a resistance of less than 1Ω was supposed to be appropriate for both voltage levels. Since the project is in a stony area, the best and cheapest technique to produce the ground electrode is to employ the ground electrode buried in the foundation. Figure 15 shows this combinational design.

Table 7. Lighting Calculations of Some Selected Parts of the Ground Floor (For Simplicity, only a Few Parts Are Shown)

No	Designation	Grid [$m \times m$]	E_{av}[lx]	$E_{\min}$[lx]	$E_{\max}$[lx]	$U_0=E_{\min}/E_{av}$	$U_1=E_{\min}/E_{\max}$
1	Counselor's room	8×16	308	260	341	0.845	0.762
2	Counselor's room	16×16	280	211	324	0.754	0.652
3	Waiting room	8×4	288	238	332	0.827	0.717
4	Waiting room	8×4	261	219	289	0.840	0.758
5	Counselor's room	16×16	315	236	356	0.750	0.663
6	Counselor's room	16×16	362	272	412	0.752	0.660
7	Waiting room	8×8	317	265	365	0.837	0.728
8	Counselor's room	8×16	322	252	373	0.873	0.676
9	Counselor's room	8×16	268	224	298	0.835	0.751
10	Counselor's room	8×16	268	232	293	0.866	0.790
11	Manager office	8×8	374	318	406	0.850	0.783
12	Electrical room	16×4	325	264	374	0.814	0.707
13	Meeting room	16×16	341	285	375	0.835	0.758
14	Kitchen	4×8	288	254	315	0.882	0.808

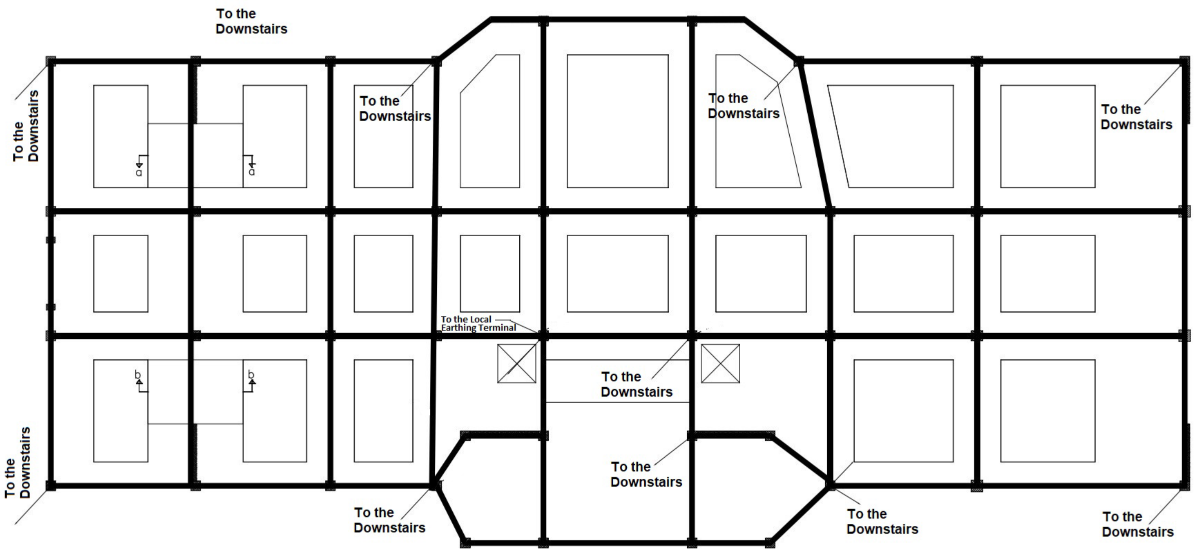

Fig. 15. Equipotential design of the last floor.

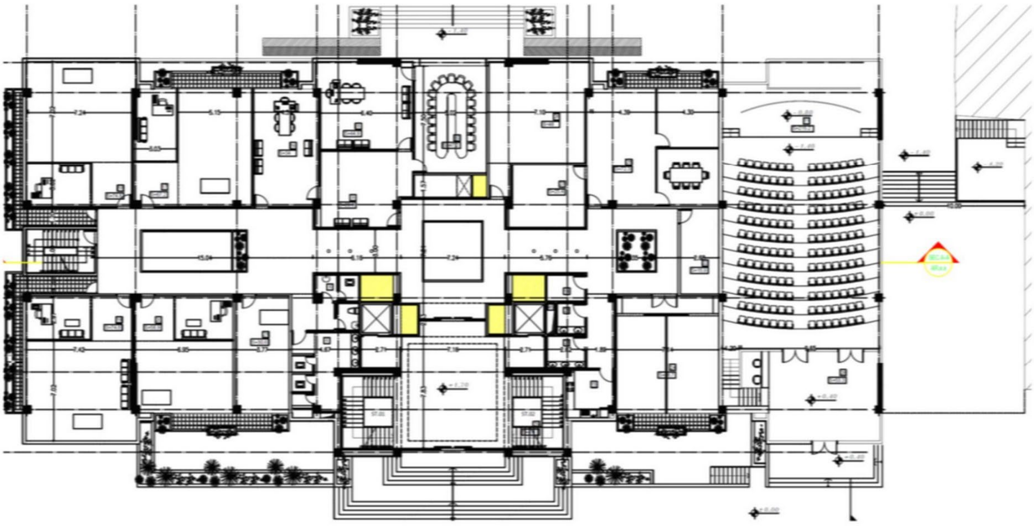

Fig. 16. Ducts considered on the ground floor.

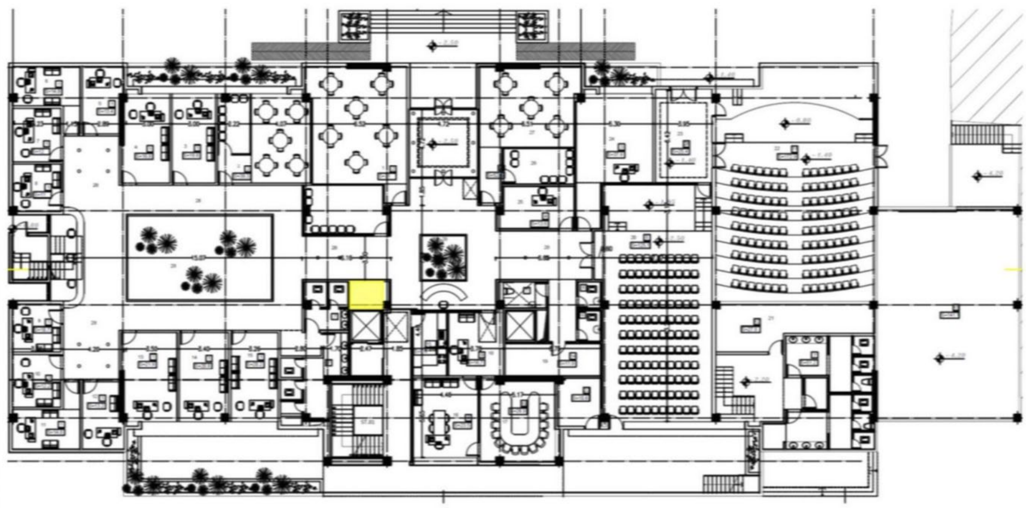

Fig. 17. The ducts considered in the floors.

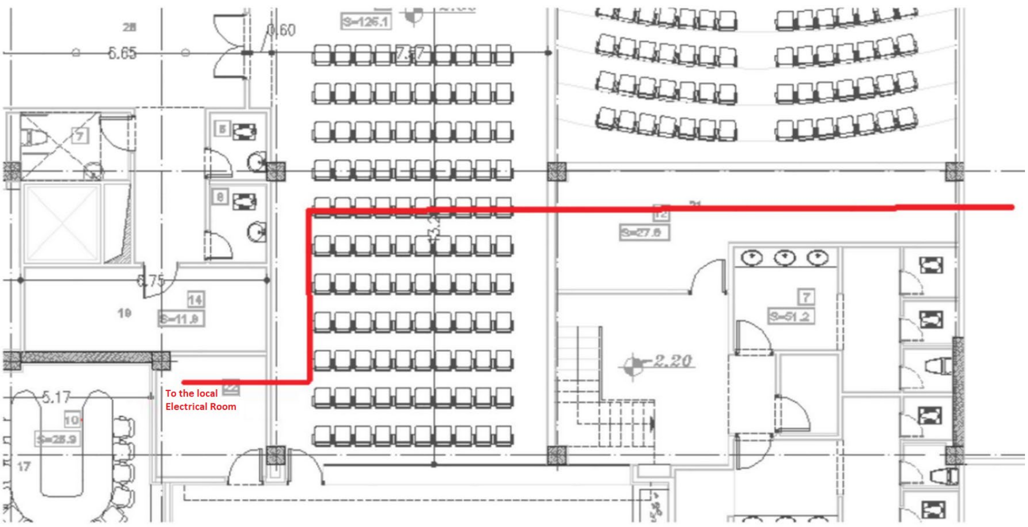

Fig. 18. The route of the main cables to the electrical room.

3.5. Risers and cable tray path

On the ground floor, only one duct was considered for the entry of electrical and mechanical facilities, and, according to the need, it was decided to divide the ducts into two categories, electrical and mechanical, with the main cables reaching the ducts through a cable tray. The number of ducts increases on higher floors. Figures 16 and 17 show the plan of the ducts considered for the ground floor and other floors.

The route of the main cables from the substation to the power distribution room and risers should also be determined with the necessary arrangements, which, according to the proposed design, involve the use of buried cables and cable trays in the specified space. Figure 18 demonstrates the path of the main cables from the substation to the electricity distribution room.

3.6. Transformer

The use of low-loss dry transformers is suggested for the main substation. According to [31], they should be selected considering the following:

- For each transformer, the maximum energy efficiency should be calculated using the load losses and no-load losses of the rated power.
- The total load loss for each type of transformer is calculated according to the value of total load power (demand power) or in other words the output load power of the transformer.
- The losses, including no-load losses and load losses, and the maximum efficiency coefficient of dry transformers under normal operating conditions and for rated power and nominal voltage of 20 kV, which are generally used in most parts of the country in the supply and feeding of building electricity with medium voltage branching, have to be calculated.

3.7. UPS and Capacitor Bank

Uninterruptible power supplies (UPS) are used to power special equipment and devices in spaces such as computer centers. During the operation of these devices, the load loss can be reduced by using devices with appropriate efficiency. The minimum efficiency for static type uninterruptible electrical devices is presented in Table 8.

The amount of reactive power flowing in the internal distribution network and the losses corresponding to it can be reduced by choosing a suitable capacitor bank. In addition, its use will bring other advantages, including an increase in the network's ability to provide active power, improvement in the efficiency of the distribution network and components of electrical panels, reduction in the cost of operation, and conservation of electricity. On the other hand, in office buildings where the level of harmonics is relatively high (usually more than 15%), it is better to use detuned inductors next to the capacitor.

The capacitor bank's capacity is estimated using the quantity of active power consumed, the average value of

Table 8. The Minimum Required Efficiency for UPS [31]

UPS rating [kVA]	Efficiency (%)
20 and lower	90
between 20 and 100	91
more than 100	93

Table 9. The Minimum Power Factor for Different Levels of the Building [31]

Energy rating of the building	The minimum value of the corrected power factor
Energy compliant building (EC)	0.92
Low-energy building (EC+)	0.94
Very low-energy building (EC++)	0.96

Table 10. How to Choose a Fire Alarm System [31, 34]

Type of building	Building of less than 5 floors from the ground floor, less than 11 units	Building of less than 5 floors from the ground floor, more than 11 units	Building of 5 to 10 floors from the ground floor, until 20 units	Building with 20 dwelling units or more	Buildings with more than 10 roofs or 5 000 m^2 area
Conventional system	Optional	Up to 16 general type alarm units and 17 to 19 independent type alarm units	Up to 16 general type alarm units and 17 to 19 independent type alarm units	Not allowed	Not allowed
Addressable system	Optional	Optional	Optional	Mandatory	Mandatory
Description	It is optional to use the fire alarm system	It is mandatory to use a type of system	It is mandatory to use a type of system	It is mandatory to use the addressable system	It is mandatory to use the addressable system

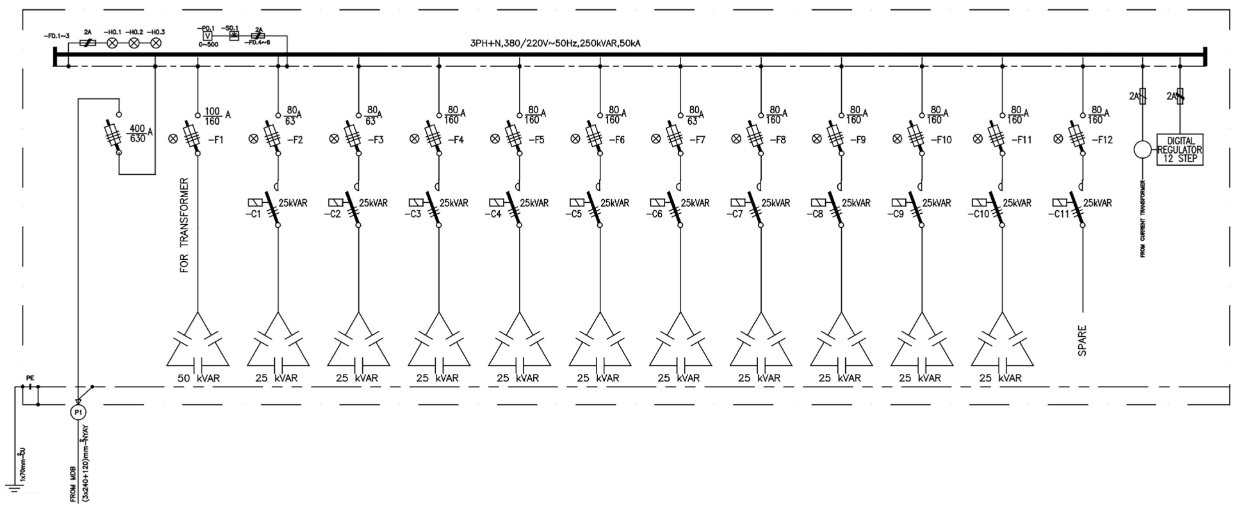

Fig. 19. Capacitor bank with 25 kVAR steps.

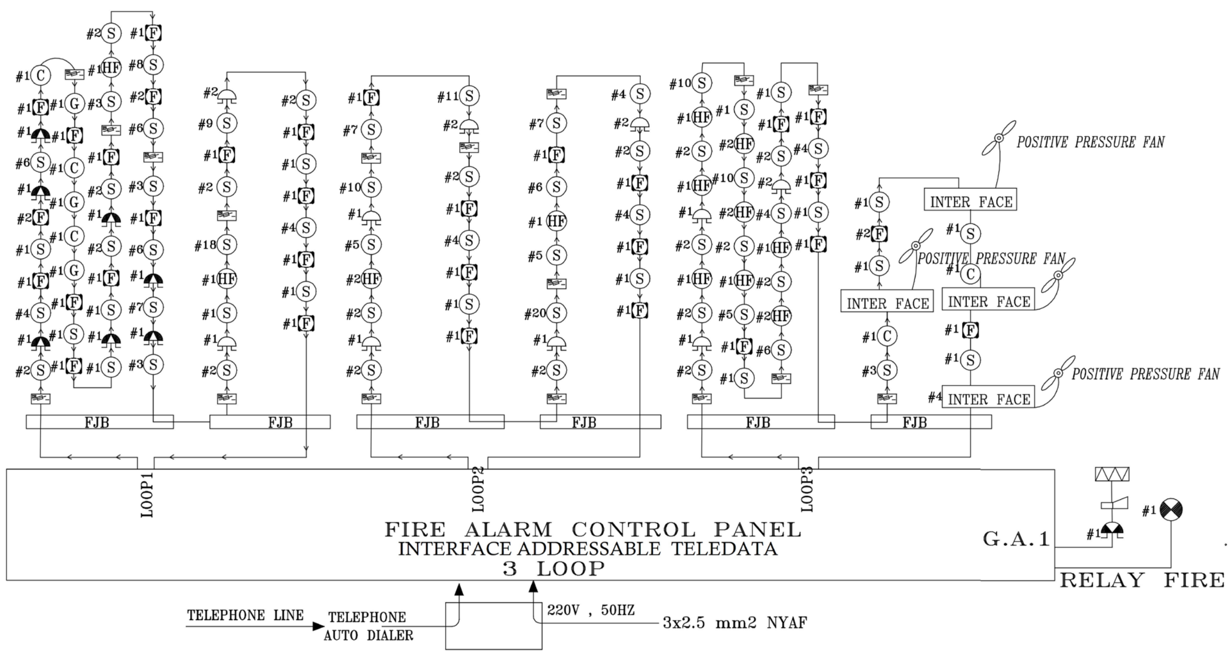

Fig. 20. Riser diagram of fire alarm-addressable system.

the power factor of electric consumers (initial coefficient), and the power grid's modified coefficient. From the point of view of reactive power regulation, according to the regulations of the electricity company, the minimum value of the power factor of the entire power supply network of the building is equal to 0.9 to measure the amount of apparent or reactive power consumption.

The amount of reactive power consumed for a power factor of 0.9 or higher is not included in the payment to the power company. The minimum value of the corrected power factor for different levels of the building is mentioned in [31] (Table 9). Considering that the faculty building is of a low-energy type, the capacitor bank should be designed so that the minimum power correction factor is equal to 0.94. By performing the necessary calculations according to the method described in [28], the capacitor capacity needed to reach such a power factor is 300 kVAR. Figure 19 shows the proposed capacitor bank with 25 kVAR steps.

3.8. Fire Alarm System

A directive on fire alarm system design was prepared in the Central Council of the Iranian Engineering System. According to an instruction mandated by the Organization of Construction Engineering System of Iran, addressable fire alarm systems are mandatory for all residential buildings with 5 floors and more, residential dwelling units with at least 11 units and more, and all buildings with more than 10 floors or 5000 m^2 area. This instruction is summarized in Table 10. According to this instruction and [31, 34], the architecture of this project's fire alarm system is addressable (Fig. 20).

IV. Conclusion

The technical feasibility studies of designing the electrical facilities of Isfahan University's virtual faculty in the form of a low-energy building were carried out in this paper. The project included various components such as a smart building management system, lighting system, a grounding and bonding system, a photovoltaic system (to supply the building's load), low-current electrical installations, transformers, uninterruptible power supplies, generators, and capacitor banks, with a required demand of 350 kW. The solar system installed provided around 30 kW through the rooftop PV system with 108 modules (6 parallel strings consisting of 18 series modules). The intelligent management system includes the lighting management system and the intelligent control of the cooling and heating systems, which use the KNX protocol for control. High-efficiency LED panels were employed in the lighting department, with the goal of consuming less than 11 W/m^2. Downlight LEDs were also utilized depending on the type of use and area, particularly in corridors with artificial ceilings. An addressable building fire alarm system was used in video monitoring and fire extinguishing facilities. In the rocky ground of the location, the grounding system and the main connection of the structure were merged and designed in the simplest and cheapest method possible. A low-loss dry transformer was utilized to feed from the public electrical distribution network. The motors were controlled by a soft starter and a multi-speed control and start-up system. Given that the faculty building is a low-energy one, the capacitor bank should be constructed so that the minimum power correction factor is 0.94. If the architectural, mechanical, and electrical design standards outlined in this paper are implemented, the building can be deemed to fall within the EC+ or low-energy building category.

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Methods for Analyzing and Increasing Cyber Resilience of Smart Energy System Facilities

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Abstract **— Energy systems are currently undergoing digital transformation. The establishment and development of an intelligent energy system involves new information technologies for monitoring, controlling, measuring, and transmitting data to control and manage power flows. However, in addition to all the advantages to be gained using modern information technology, it becomes possible to carry out cyber-attacks on energy facilities. The purpose of this work is to review methods designed to analyze and enhance the cyber resilience of Smart energy system (SES) facilities. Various methods have been used to date, which, to one degree or another, can be used to achieve the above goal. The paper discusses in detail the methods, which can be utilized to:**

- **evaluate the risk of cyberattack;**
- **assess the consequences of cyberattacks;**
- **counteract cyberattacks;**
- **assess cyber situational awareness, and the ways to increase the cyber resilience of SES facilities.**

The paper also presents the problems facing information security and their causes, and proposes solutions to improve cyber security of electric power facilities.

Index Terms**: smart energy system, cyberattack, cybersecurity, resilience of energy system.**

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I. Introduction

Smart energy system is an integration of classical technologies for energy generation, conversion, transmission and distribution, and modern information and communication computer technologies. Numerous operating parameters to be controlled and structure of the SES require the development and massive implementation of reliable, secure (protected from various kinds of interference), and high-speed information transmission systems. However, this creates conditions for accidental and uncontrolled impacts on the SES components and facilities. There is a possibility of cyber-attacks on energy facilities, and in this regard, the issue of cyber security is acute [1].

The concept of cybersecurity includes the prevention of damage, unauthorized use of information- communication networks and systems, and the information contained in them; the operation with guaranteed confidentiality, integrity, and availability of information, as well as its restoration and recovery of data communication networks in the event of a malicious attack or natural disaster. The main objective of the cybersecurity system in the electric power industry is to protect it against deliberate violations of information and technological security that can be launched by employees of the energy company, industrial spies, or other persons interested in hacking and penetrating the automated process control system (APCS) of the SES facility.

The advent of the first APCS at energy facilities brought about a pressing need to ensure cybersecurity. Cybersecurity threats at the information control system (ICS) level can be posed as weak points where system control can be accessed. The main types of information security threats in APCS are:

- Threats of unauthorized access to critical information by intruders – 57%;

- Threats of malware introduction into software and hardware components of automated process control systems – 36%;
- Threats of network attacks such as "denial of service" – 7% [2].

A “successful” cyber-attack allows attackers not only to obtain confidential data about the production process, but also to stop it. In this regard, the past few decades have seen actively conducted research on this topic. The study and analysis of the vulnerabilities of the ICS and its response to external influences, and the development of protection measures can significantly reduce and even prevent the risk of occurrence and development of the possible consequences. To this end, various methods for analyzing the cybersecurity of an energy facility are currently being developed [3–9], which are part of a more general method that considers the problem of cyber-physical stability of objects.

II. Methods for Analyzing the Cyber Resilience of SES Facilities

1.1 Methods for evaluating the risk of CAs

A cybersecurity system should be constructed so that it could be possible to take into account the implementation of cyber-attacks on the control systems of energy and industrial facilities from various sources, among which are the following [2]:

1. Internal (employees, suppliers, contractors);
2. External random (undirected);
3. External intentional (directed).

The main goals of cyber-attacks on the control systems of SES facilities are:

- to disrupt the production process by blocking or replacing information flows;
- to cause damage, blockage or shutdown of equipment, which may lead to a stoppage of production, a threat to human life or a negative impact on the environment;
- to use a disguise by sending erroneous information to operators, stimulating them to perform erroneous actions, which may be accompanied by negative consequences;
- to recommend to change the software configuration or equipment settings to disable SES components and systems;
- to transfer malware to the system (software designed to penetrate a computer without the informed consent of its owner);

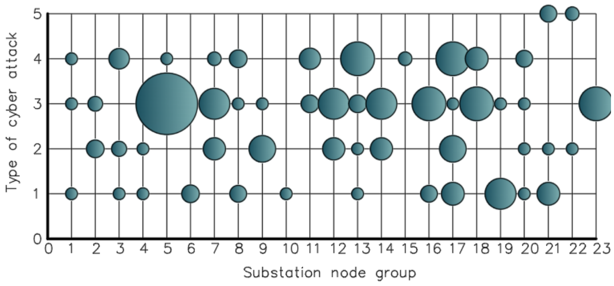

***Fig. 1. Economic impact assessment diagra*m** [12].

- to change the settings of security systems.

Examples [10, 11] provide several methods for analyzing possible cyber-attacks on SCADA systems. The paper [10] presents a method for measuring the risk of attacker’s manipulation of the system control process, the consequences of a violation of a controlled physical process, as well as the vulnerability of a SCADA system to malicious intrusion. This method involves applying Petri net’s state coverability analysis combined with the modeling process. These problems are solved by determining first the potential process failure conditions and examining the operational consequences of each process failure. Secondly, the SCADA failure modes that can cause corresponding process crash are found out for each identified process failure. Finally, we identify for each SCADA failure the network resources over which an adversary would need to exert control in order to induce the corresponding SCADA failure. Considering the initial state of a network attack, the method provides for the identification of network resources through which an attacker can potentially gain control. Thus, the risk is measured as a failure of process operational consequences function and propensity to induce process failure due to an attacker gaining control over the network resources during an attack.

In the paper [11], authors propose a mathematical model for determining the financial losses resulting from CAs on a computer-based information system used in industrial plants. The study suggests seven possible types of attacks (replay capture, spoofing, denial of service, etc.) and indicates six types of losses that an attack can cause (control loss, product loss, staff time loss, etc.) along with the probability of the type of loss for each type of CAs. The paper presents a formula for calculating the losses of each type. The cost of prevention, for example, is calculated as the product of the cost of upgrading the components that are resistant to a certain type of attack and the probability of loss of prevention for a given type of attack. Ultimately, the total estimated loss of income from all types of CAs can be calculated using the model presented in the paper.

1.2. Methods for assessing CA consequences

Successful CAs can differ in their consequences and methods of action. The paper [12] presents a method for assessing the technological consequences of cyberattacks. This technique is designed to identify the nodes and objects of the energy system with the most severe economic consequences from cyber-attacks. In addition, this technique makes it possible to determine approaches to choosing the optimal architecture to build operational safety systems for energy facilities.

The method consists of the following steps:

1. Analysis of primary and secondary equipment;
2. Analysis of the CA types;
3. Calculation of cost indicators;
4. Construction of an evaluation diagram (Fig. 1).

To apply this method, it is necessary to understand which SES components are susceptible to CAs. The paper considers a 500/220/10 kV digital substation as an example. The following groups of nodes of this substation were identified separately for each voltage class:

1. Switching equipment;
2. Digital current and voltage transformers;
3. Converters of discrete signals;
4. Relay protection and automation equipment;
5. Bay controllers;
6. Process bus communication front-end equipment;
7. Measuring equipment;
8. Time server;
9. Station bus communication front-end equipment;
10. Telemetry controllers;
11. SCADA server;
12. Workstation (AWP);
13. Communications equipment.

This method also requires information about the types of possible CAs (for example, spoofing, DDoS attack, classical file virus infection, etc.) that can be applied to SES components.

The parameters determined for each group of nodes are:

1. Potential for a CAs;
2. Possible technological violations;
3. The timing of the CA consequences.

In addition, this method can be used to assess the cost of restoring components after CAs have happened. Calculation of the cost indicators of the CA consequences with this method takes into account the following:

1. Costs of emergency recovery work to repair failed equipment;
2. Shortfall in the compensation for electricity losses;
3. Additional costs of the electricity generation and transmission;
4. Economic damage due to false information transmitted to remote control.

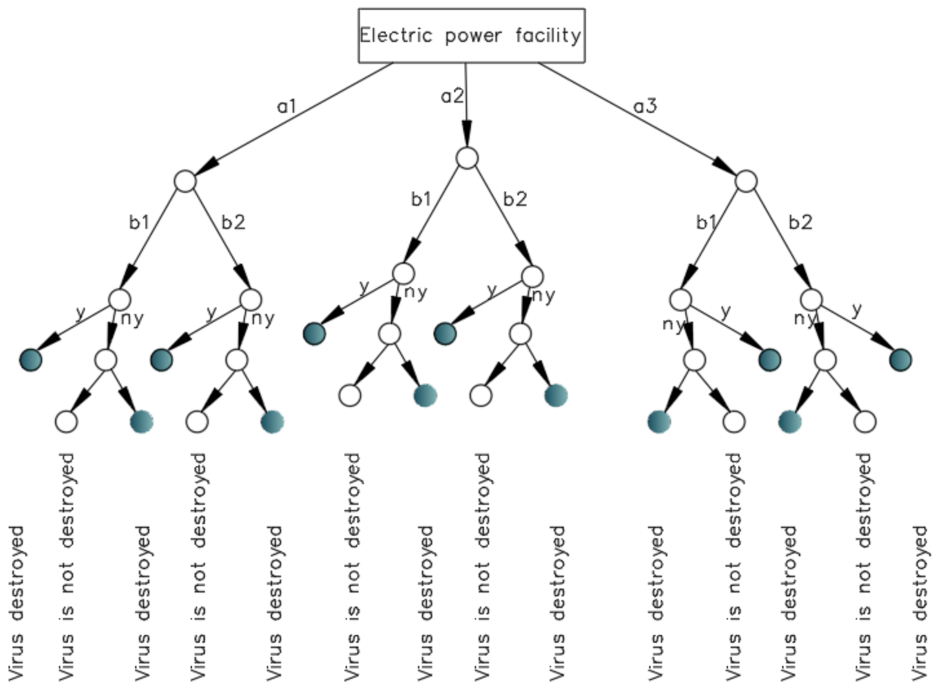

***Fig. 2. Tree of possible outcomes of a hacker attack* [1].**

Based on the data obtained above, a diagram (Fig. 1) is constructed to show the nodes of electric power facilities to encounter the most severe economic consequences of CAs.

1.3. Methods for counteracting CAs

The methods designed to simulate a CA on an energy facility are also common. The process of simulation involves development of various attack scenarios and assessment of the damage of their consequences.

The paper [1] describes the process of modeling the neutralization of hacker attacks by building a tree of possible outcomes (Fig. 2).

It is assumed that Party A (hacker) attacks the APCS system of an electric power facility by infecting it with a virus, and uses three options of viruses: a1, a2, a3. Party B organizes defense in two ways: b1, b2. Move 1: Party A chooses one of the attack options a1, a2, a3. Move 2: Party B chooses one of the options b1, b2 to protect the object. Move 3 (random): the information security system bj destroys (y) or does not destroy (ny) the virus ai. If the ai virus is neutralized, the game is over. If the ai virus has broken through to the APCS system, then the next move follows.

Each path from the initial vertex to the final vertex corresponds to one of the game variants. The number of possible game variants (games) is equal to the number of pendant vertices. As seen from Fig. 2, there are 18 possible games in the considered game. The marked 12 pendant vertices correspond to favorable outcomes of the game, when the protection of the electric power facility is effective.

This model can be used to simulate a cyber-attack on a designed or already built energy facility in order to find weaknesses in protection systems.

1.4. Methods for assessing cyber situational awareness

It is also important to emphasize that the vulnerabilities of energy facilities to CAs are currently being investigated within the framework of an approach called cyber situational awareness (CSA) [13–15]. CSA is a field of research related to the application of artificial intelligence methods in the field of cybersecurity, aimed at increasing awareness of possible situations of cybersecurity breaches and automatic detection of cyber threats. The paper [15] presents a method for analyzing CSA of an energy facility, which includes the following steps:

1. Analyze cyber threats of energy infrastructure;
2. Model scenarios of extreme situations in the energy sector caused by the implementation of cyber threats;
3. Assess the risks of violating the cybersecurity of the energy infrastructure.

Within the framework of the methodology, the authors propose to apply semantic methods to analyze the impact of cyber threats on energy facilities in terms of energy security. The semantic methods show their high performance in the absence or incompleteness of data when modeling the behavior of systems that cannot be formally described or fairly accurately predicted. An approach to the analysis of CSA of energy objects is presented as a synthesis of cybersecurity and situational awareness studies, characterized by the use of semantic modeling.

III. Information Security Problems Facing Electric Power Facilities and Their Causes

Nowadays, the computing systems of power facilities have a high degree of integration and widely use digital communications based on open international standards, such as IEC 60870, IEC 61850, and IEC 61970. Increasing the connectivity and awareness of individual subsystems made it possible to significantly boost the capabilities of protection and control systems, to make them smarter and more efficient to use. Furthermore, the use of standardized approaches and tools has significantly reduced the cost of integration and ensured a higher degree of functional reliability.

Specialists of the Kaspersky Laboratory published a report on the information security problems at electric power facilities and their causes [16].

2.1 Open communications

Open and unsecured communication channels between the components of protection and control systems, as well as between power infrastructure facilities:

- Lack of authentication;
- Open standards and open data transfer;
- High detail of network communications;
- Communication with open networks.

2.2 Service personnel's lack of information security knowledge

A limited number of specialists maintain a large fleet of devices, which are situated at facilities that do not have permanent staff and are often distributed over a vast area. Moreover, these personnel often lack even basic knowledge in the field of information security:

- Privileged remote access from an untrusted network;
- Lack of password protection and user management policies;
- Outdated software;
- Service from unsafe workstations;
- Lack of regular control of hardware and software.

2.3 Information security requirements are not complied with

Devices, software, and systems based on them are developed and created without considering information security issues.

- Poor resistance to hacking;
- Incorrect or insufficient LAN security settings;
- Lack of protection of data transmitted through open channels;
- Lack of role-based access rights;
- Lack of solutions to control the launch of applications;
- Absence or insufficiency of tools for information security event registration.

2.4 Difficulties of contractor access control and differentiation

A common practice is to carry out certain types of maintenance by contractors. In this regard, the issue of providing temporary access to a limited amount of equipment without the possibility of influencing other parts of the system, as well as canceling such access upon completion of work, is essential.

2.5 Long service life of vulnerable components

The service life of devices and of control and protection systems is long (20–30 years). Thus, insecure systems that continue to be introduced at present will not be replaced until several decades later. A phased partial upgrade is extremely difficult, since secure solutions (for example, using encryption) are incompatible with conventional, vulnerable solutions. In view of the foregoing, there is obviously a systemic problem, which is as follows:

- Modern systems for protection and control of power system equipment are neither isolated from the outside world, nor are systems with a closed implementation;
- ACSs do not have sufficient built-in information security tools;
- Detection of illegitimate information impact, active or past, in the current context is organizationally and technically extremely difficult;
- If such an impact has been detected, it is not clear how to respond to it and what measures to take.

IV. Ways to Increase the Cyber Resilience of SES Facilities

In order to enhance the cyber resilience of SES facilities, it is necessary to eliminate the problems indicated in the second chapter. Cybersecurity is increased through such measures as fixing the vulnerability of access channels, introducing adequate information security procedures and processes, as well as using special technical solutions based on firewalls [1]. Since the functioning of SES facilities involves constant interaction of its constituent components, the effect of destabilizing factors that led to the failure of some components can have (and in most cases has) an impact on the performance indicators of components that are not directly affected by this effect. The flow diagrams of most of these objects are implemented with rather "rigid" structures, which allows external influences to spread (cascade development). Naturally, in this case, the reliability indices of both individual components and entire system are reduced, which can lead to a shutdown of the consumer's technological process or its transition to a partial operability mode. In accordance with the well-known approaches to improving the reliability of energy facilities and their components, it is not possible to duplicate all the components most vulnerable to the impact of destabilizing factors.

The paper [17] analyzes the ability of a digital substation (one of the key components of modern SES) to withstand cyber-attacks and restore its working state after their impact. The paper proposes the following steps to boost the resilience of such substations:

- Improve the quality of software for digital substation. In terms of authorization tools, access control, firewalls and other similar tools, various errors are found in the software every month, including those affecting its security. To increase security, it is necessary to guarantee the correctness of dedicated software for the digital substation.
- Provide functional decomposition and physical separation of information flows. Successful cyber-attack on certain digital substation nodes can disrupt many functions. This step would significantly reduce the damage from cyber-attacks.
- Enhance the quality of digital substation design. High-quality design of devices, modules, and programs, and then modeling of threats and attacks on these designed and upgraded devices, modules, and software will increase the cyber resilience of the digital substation.

At this stage, secure communication, strong user authentication, permission (access), logging and reporting should be thought out. Consideration of the most likely attack scenarios requires the identification of vulnerabilities in network services and applications, as well as the assessment of the degree of resilience of network components and possible damage. When modeling attacks on link layer protocols, the cyber resilience of the network at the link layer level should be checked. It is crucial to involve top cybersecurity experts when developing and testing equipment and software for the digital substation. Ensuring cyber resilience of the digital substation in the face of cyber threats, should involve, at least, the following steps:

- Carrying out dynamic analysis of network and application traffic of the TCP/IP protocol stack, and using intrusion detection and prevention systems, since well-known anti-virus programs and firewalls are effective only for protecting obvious network access points.
- Providing correct configuration of firewalls, especially those enabling access to global networks. This can be achieved by organizing inter-network separation using simplex channels instead of duplex ones, with appropriate communication protocols, converting digital information to analog signals, and then analog signals back to digital information.
- Performing regular technological testing to identify existing vulnerabilities in IT infrastructure components for the corporate network perimeter (external test) and for internal resources (internal test).
- Checking the stability of routing, etc.
- Using High Availability Seamless Redundancy and Parallel Redundancy Protocol, the latest additions to the IEC 62439 standard for high availability industrial Ethernet networks. Designed for mission-critical and time-sensitive applications such as substation automation and traffic control, HSR and PRP provide guaranteed behavior in harsh environments and increased network reliability.
- Ensuring remote configuration/parameterization, monitoring, remote SCADA communication, remote diagnostics and firmware updates are becoming important requirements for intelligent electronic devices (IEDs). The security of the communication line is an imperative condition for remote firmware updating.
- Providing network segmentation and protection of remote communication channels by creating encrypted tunnels to prevent an intruder from having full access to device settings.

V. Conclusion

The creation and development of a smart energy system involves the introduction of new computer technologies for controlling, measuring, and transmitting data for monitoring and managing operation of the system. However, in addition to all the advantages gained through these implementations, the vulnerability of energy facilities to cyberattacks increases. Therefore, apart from the conventional challenges of enhancing the efficiency of electricity production, conversion, transmission, and distribution; and improving reliability, security, and resilience of smart energy systems, it is also crucial for them to address the concerns regarding their cybersecurity. This paper presents a review of modern methods for analyzing the cyber resilience of SES facilities and the methods to improve it.

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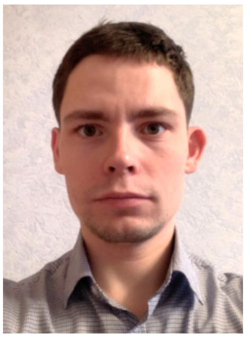

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