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SUBSTANTIATION OF THE WAYS OF USING RENEWABLE ENERGY SOURCES IN THE POWER SUPPLY SYSTEMS FOR NON-TRACTION CONSUMERS OF RAILWAY ELECTRIC MAINS

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INTRODUCTION

Currently, non-traditional power sources occupy an increasing volume in the energy market in Ukraine, namely bioenergy, heat pumps, geothermal heat, solar energy, small hydropower. Now renewable energy sources (RES) are developing rapidly, the number of suppliers is increasing and the conditions for providing electricity supply services are changing[1].

Over the past few years, Ukraine has made significant progress in the development of renewable energy sources, namely solar and wind power plants. Regarding the possibilities of using unconventional energy in the power supply systems of non-traction consumers of railway power grids shows several possible areas: 1) power supply system from the external power system, which, along with traditional, operate in parallel and renewable energy sources; 2) use of renewable energy to supply infrastructure[2] and consumers' own needs[3]. Particular attention is paid to areas where the external electricity supply of railways is unstable, so the use of renewable energy sources to meet the needs of non-traction consumers is an important task. As is known[4], at present, advanced

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[1] Vijay D. (2013) Solar energy: Trends and enabling technologies [Text]. *Renewable and Sustainable Energy Reviews*. vol. 19, pp. 555–564.

Ryoichi K. (2014) Assessment of massive integration of photovoltaic system considering rechargeable battery in Japan with high time resolution optimal power generation mix model [Text]. *Energy Policy* / vol. 66, pp. 73–89.

[2] Takaki K. (2014) Demonstration Experiment for Energy Storage and Rapid Charge System for the Solar Light Rail [Text]. *Energy Procedia* / vol. 57, pp. 906–915.

[3] Сиченко В.Г., Бондар О.І., Прихода М.С. Аналіз впливу сонячної генерації на роботу тягових підстанцій електрифікованих залізниць. *Світлотехніка та електроенергетика*, 2015, № 1(41). С. 10–17.

[4] Коновалова А.А. Потенциал возобновляемой энергетики для Южно-Уральской железной дороги. *Энерго- и ресурсосбережение. Энергообеспечение.*

world technologies are being introduced into the power supply systems of railway transport, namely the integration of additional renewable energy sources into the existing electrical network. At the same time, a systematic approach is used, aimed at using the potential of wind and solar energy in the railway infrastructure.

The main task of the railway transport of Ukraine is its high-quality and efficient functioning to meet the needs of industry and citizens of the country in safe transportation. At present, in the conditions of constant growth of the cost of electric energy and fuels and lubricants, traditional energy sources do not meet the growing needs. Ukraine is creating various programs for the introduction of energy-saving technologies, the main purpose of which is to save energy resources, reduce the necessary investment in the fuel and energy sector, as well as reduce the harmful effects of energy production on the environment. Therefore, the introduction of alternative energy in the power supply systems of railway transport is a topical issue[5].

The production of electricity using renewable sources (wind farms, thermal power plants, biomass) for 12 months of 2019 amounted to 5542.2 million kW·hour, which is 2909.5 million kW·hour, or 110.5% more than for the corresponding period of 2018. And this share is equal to 3.6% of the total amount of energy produced in Ukraine during this period[6].

Continuous improvement of wind power plants and technologies of their production opens all new areas of application, including for power supply systems of non-traction consumers of railway transport.

Нетрадиционные и возобновляемые источники энергии: материалы Международной научно-практической конференции студентов, аспирантов и молодых ученых, посвященной памяти профессора Данилова Н.И. (1945–2015). Даниловских чтений (Екатеринбург, 11-15 декабря 2017 г.). Екатеринбург : УрФУ, 2017. С. 804–807.

[5] Сущенко К.Б. Оптимізація споживаної електроенергії при застосуванні нетрадиційних джерел живлення. *Електромагнітна сумісність та безпека на залізничному транспорті*. 2017. № 14. С. 80–85. DOI: 10.15802/ecsrt2017/137789.

[6] Electricity production in Ukraine. URL : https://kosatka.media/uk/category/elektroenergiya/analytics/proizvodstvo-elektroenergii-v-ukraine-u-vie-znachitelnyy-rirost.

1. Specifying the need to use renewable energy sources in the power supply systems for non-traction consumers

It is known that sustainable development of the world economy is impossible without the reliable energy supply for enterprises and households of any country. However, growing demand for energy transforms it into the global problem due to the limited amount of fossil fuel on our planet and insufficient efficiency of the technologies used for the fuel processing to obtain the required energy types. In this context, intense energy-related contamination of the environment has reached critical degree of the anthropogenic influence on the nature.

Despite the fact that production, transport, agriculture, and household usually use different energy types (electric, thermal, light, and mechanic), it is the electric energy that is the most widely used one owing to its convenience for transportation, distribution, and use. This energy is characterized by high efficiency of its conversion into other mentioned energy types and simple structure of the facilities required for that.

Despite the indicated advantages, electric energy has considerable disadvantages which are characterized by very low efficiency of its generation by modern electric power stations, using the thermal conversion cycle, and complexity of the time matching as for its production and consumption. One more rather important problem here is great amounts of the accumulated electric energy.

Unreliability of electric supply for its end-users is stipulated by one more defect of electric mains as they are being modernized (especially, in Ukraine) quite slowly comparing to their deterioration. Unfortunately, the electric main accidents occur more and more often; due to that, small settlements located near the railway stations and being the majority of non-traction consumers, suffer from such situations. Moreover, that is often accompanied by inadmissible current deviations to both sides.

The mentioned overvoltages and undervoltages in the electric mains relative to their admissible values (upper is 242 V; lower is 198 V) result in the additional (apart from the ones caused by the traction railway consumers) sinusoidal form distortion and impulse kilovolt interferences[7]. At best, it is the cause of more frequent disconnections of non-traction consumers; at worst, that results in the failure of electric equipment.

[7] ДСТУ 3466-96 Якість електричної енергії. Терміни та визначення. Київ, 1998. 22 с.

Poor-quality electric supply of non-traction consumers from the electric mains as well as their considerable remoteness from the centralized power supply lines force to search for other suitable ways to get electric energy. Most commonly, those are autonomous sources based on diesel or petrol generators. They are rather quick to bring into operation as well as simple and reliable to operate. However, they have certain disadvantages limiting the demand for such plants by the necessity to have so-called switching facilities.

The main disadvantage is that such generators use expensive fuel. That results in the considerable prime cost of the produced electric energy comparing to the current energy market tariffs[8]. Besides, the prime cost is higher in case of lower-capacity diesel or petrol generators than in case of higher-capacity ones, while the practice shows that it is expedient to use 5-10 kW autonomous sources without the re-equipment of the available mains for energy consumers.

Taking into consideration the current electric energy tariffs, the prime cost of such energy supply will be by 2-4 times (in the first case) and by 3-11 times (in the second case) higher depending on the amounts of its generation by diesel or petrol generators[8]. Even constant increase in the electric energy cost by the National Commission for State Regulation of Energy and Public Utilities will not make the autonomous electric supply based on fossil fuel to be economically expedient at an early date.

Low level of environmental friendliness of such systems is their one more important disadvantage. While burning, the fuel emits significant amount of toxic components and cancerogenes into the atmosphere with further negative effect on the human health. In addition, diesel and petrol generators are characterized by poor noise features. That deteriorates the whole ecological situation.

Taking into consideration the aforementioned, it is quite clear why the demand for electric supply systems using local renewable resources has grown recently. The world started implementing such systems last century; Ukraine began showing interest in those systems only after considerable growth of energy tariffs and adopted Law on so-called

[8] Тарифи на електроенергію для домогосподарств України. URL : http://www.nerc.gov.ua/data/filearcli/catalogl/Prezentatsia_optymizatsia_taryfiv_na_electro.pdf.

"green" tariff[9] as the latter means financial stimulation of the energy market participants which use the renewable energy sources (RES).

"Green" tariff means the state-fixed price to purchase electric energy produced by RES. As a rule, the "green" tariff exceeds considerably the market value of electric energy from the "traditional" energy sources. That is explained by the meaningful state policy to stimulate private investments in the renewable energy sector and to increase its share in the total energy balance of the state.

Nowadays, Ukraine is being involved in the process. For the recent years, it has demonstrated considerable progress in the issue of the development and use of renewable energy sources, i.e. solar and wind plants[10].

Thus, the implementation of "green" tariff, which current values are shown in Table 1, may be considered expedient and timely.

Table 1

"Green" tariff values for electric energy

Type of alternative energy	**Tariff, kop./kW·hour**
Wind energy	122.77
Solar energy	505.09
Electric energy from biomass	134.46
Water energy (mini HES)	84.18

"Green" tariff in terms of solar electric power stations is being constantly corrected; nowadays, it is reduced considerably.That is done for the objects commissioned after 01.01.2013 and in the differentiated form: for ground solar power stations – by 27%; for stations with the capacity of more than 100 kW mounted on roofs or walls – by 22%; for the same stations but with the capacity of less than 100 kW – by 16%.

Numerous Ukrainian scientific and business institutions are dealing with the problem of complex RES implementation and improvement of RES efficiency; the main one is the Institute of Renewable energy (IRE) of the National Academy of Sciences of Ukraine. Such famous national

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[9] Закон України «Про електроенергетику»: редакція від 01.01.2019. Верховної Ради України. URL : https://zakon.rada.gov.ua.

Закон України, щодо встановлення «Зеленого» тарифу. URL : http://zakon4.rada.gov.ua/laws/show/601-17.

[10] Національний план дій з відновлюваної енергетики на період до 2020: редакція від 01.10.2014. / Кабінет Міністрів України. URL : https://zakon.rada.gov.ua/laws/show/902-2014-%D1%80.

scientists studied that problem in their numerous works: P.D. Lezhniuk, S.O. Kudria , V.V. Kaplun etc. Their studies cover the problems of improving the conversion efficiency of such energy; compatibility of such systems with the centralized networks; possibility of their involvement to control the load curve of the latter; and the problem of the alternative-source energy accumulation[11].

Currently, there are following reasons to transfer for RES:

– Global and environmental ones based on the well-known and proved fact of negative environmental impact of the energy generation technologies (including nuclear and thermonuclear), which application will inevitably result in the catastrophic climatic changes right within the first decades of the 21st century;

– Political ones stipulated by the fact that the country, being the first to master alternative energy, will claim to be the first in the world and not to depend on the prices for fuel resources;

– Economic ones as the transfer for alternative technologies will make it possible to save national organic resources for their further use in chemical and other industries. Moreover, today cost of the energy produced by numerous alternative sources is lower than its cost from the traditional sources; the payback period of the projects with the use of alternative sources is quire shorter as well. The price of alternative energy is reducing rapidly while the one of traditional energy is growing.

– Social ones due to the fact that population number and density is growing constantly, and it is rather difficult to find a place for the construction of nuclear power stations and hydroelectric stations where energy generation would be cost-effective and safe for the environment and human. It is well-known that the regions with the mentioned stations and

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[11] Лежнюк П.Д., Комар В.О., Кравчук С.В., Котилко І.В., Прокопенко І.О. Оцінювання якості електропостачання в локальних електричних системах з різнотипними відновлюваними джерелами енергії. *Вісник Харківського національного технічного університету сільського господарства. Серія «Проблеми енергозабезпечення та енергозбереження в АПК України».* № 195. 2018. С . 23–25.

Кудря С.О. Стан та перспективи розвитку відновлюваної енергетики в Україні. *Вісник Національної академії наук України*. 2015. № 12. С. 19–26. URL : http://nbuv.gov.ua/UJRN/vnanu.

Каплун В.В. Удосконалення перетворювального агрегату комбінованої системи електроживлення з поновлюваними джерелами енергії. *Електро-технічні та комп'ютерні системи*. 2016. № 22(98). С. 165–169. URL : http://etks.opu.ua/core/getfile.php?id=l 810.

enterprises of fuel and energy complex have high rate of oncological and other serious diseases. Apart from that, huge plain hydroelectric stations do great harm. Those factors are the reasons for growing social strain.

– Evolutional and historical ones related to the limited fuel resources on the Earth as well as exponential growth of catastrophic changes in the planet’s atmosphere and biosphere due to their use. Besides, the available traditional power system is considered to be the dead-end one; thus, the human evolution needs to start immediately its transfer to the renewable energy sources.

Consequently, taking into consideration current important problems of non-traction consumers of railway electric mains due to the considerable dispersion of their power systems and extremely poor energy quality in them along with rather high potential of local renewable energy resources, it is quite expedient to study the possibility to use RES as the necessary component of the supply for electric power consumers considered in this paper. In this context, it is urgent to pay attention to those functions which the specific power system performs, i.e. what kind of function it should be.

A system of electric supply involving RES may be main-operated, hybrid, and autonomous. Main-operated systems are the separate electric stations constructed on the RES which transfer all the generated electric power to the energy market according to the mentioned “green” tariff. While their constructing, the number of inverter substations are reduced maximally by using the most powerful equipment to reduce the length of proper electric mains, thus reducing the possible losses.

Currently, the available and most widely used invertors in the market are with the capacity of 500 kVA and 630 kVA. Thus, each typical of traction substation (TS) uses two converters of that type which are connected with a three-winding transformer with the capacity of 1000 kVA and 1250 kVA respectively.

Hybrid systems are used when there is the need to reduce electric power consumption from the traditional main and sell the unused energy from the renewable sources according to the “green” tariff. They are not designed to use batteries. Moreover, such electric stations cannot provide a consumer with energy at any time or be the only one power supply source. Generating capacity of a hybrid electric station for private individuals cannot be more than 30 kW – maximum admissible value in terms of their connection to the “green” tariff.

In case of the autonomous power supply systems, constructed on the RES, they are used when it is economically inexpedient to be connected to general mains due to considerable remoteness from these mains. In most cases, such systems may be uneconomical as it is impossible to sell the excessive generated electric energy according to the "green" tariff and it is required to use great amount of storage batteries (SB) for guaranteed power supply for consumers at any time.

It is obvious that hybrid stations may be the most expedient in the power supply systems for non-traction consumers. However, like the autonomous ones, those systems will not be able to use stimulating advantages of the "green" tariff. Thus, their energy generation in terms of higher (than the current tariffs) prime cost may be explained only if other costs are reduced, e.g. to improve energy quality up to the level when it will be much better than in the railway mains.

2. Example of current RES use in the power supply systems for non-traction consumers

Currently, we know the cases of RES use in the power supply systems for both traction and non-traction[12] consumers of railway networks. Taking the latter as the example, identify its objectives and results.

Previously, a scheme represented in Fig. 1 was used to supply power for the systems of railway automatics, i.e. devices of signaling, centralization, and blocking (SCB)[13] at the Verkhivtsevska distance of Prydniprovska Railway. The power was supplied from the buses of own needs in alternating current. In this context, voltage of 400 V was increased by a transformer up to 10 kV and sent to the special buses, from which it was supplied to the corresponding power supply sites of railway loads along 10 kV feeders.

According to the represented scheme, double transformation was used to supply power for SCB devices[14]: first, voltage was decreased down to 400 V with the help of TID; then, it was increased up to the same 10 kV.

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[12] Качан Ю.Г., Кузнецов В.В. Щодо практичного застосування відновлюваних джерел енергії в системах живлення нетягових споживачів. *Гірнича електромеханіка та автоматика. Науково-технічний збірник*. № 102. Дніпро, 2019. С. 21–25.

[13] Собственные нужды подстанций. Электросети. URL : http://pue8.ru/elektrotekhnik/903-sobstvennye-nuzhdy-podstantsij.html.

[14] Прохорский А.А. Тяговые и трансформаторные подстанции. Москва : Транспорт, 1983. С. 436–441.

That was used for electric disconnection between the collecting buses 10 kV and power lines 10 kV of SCB.

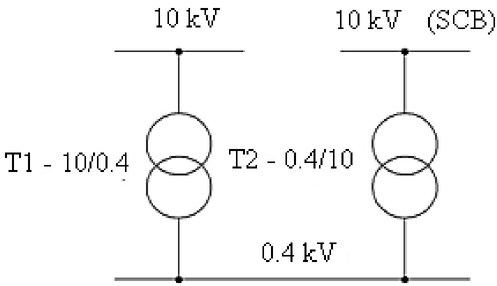

Fig. 1. Previous scheme of power supply for the systems of railway automatics

In the case under consideration, the represented scheme was complemented by the implemented solar electric power station (SEPS) according to the variant shown in Fig. 2. As it is seen from the new scheme, use of additional rectifier B and inverter I break not only electric but also electromagnetic connection of collecting buses and SCB lines.

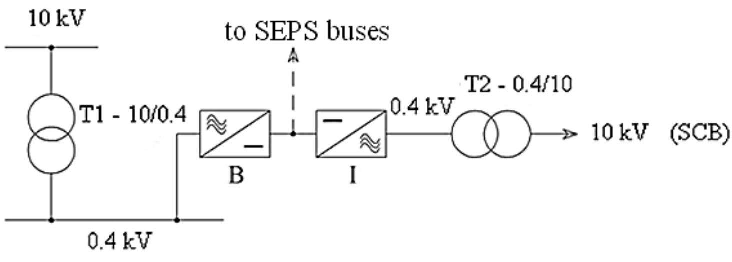

Fig. 2. The proposed scheme to supply power for railroad automatics

Solar electric power station was designed basing on the average needs of the indicated consumers; that was 44144 kW·h per month, being 1424 kW·h per day. The most cost-efficient photovoltaic converter SP500M6-96 of that time was selected; Table 4.2 shows its main electric and mechanical characteristics.

Knowing the required capacity of SEPS and the selected photo module, the necessary number of the latter was determined:

$$N^{SE} = \frac{P^{SEPS}}{P_{\max}^{SE}} = \frac{59333}{500} \approx 120 \text{ pieces.}$$

Then, taking into account the input inverter voltage, the required number of circuits with the successively connected modules was specified:

$$N_{successively}^{SE} = \frac{U_{inv}}{U_{\max}^{SE}} = \frac{260}{48,63} \approx 5 \text{ pieces.}$$

In this context, the required number of the paralleled circuits was defined in terms of the capacities of each of them and the whole system:

$$N_{paralleled}^{SE} = \frac{P_{\max}^{SEPS}}{P_{successively}^{SE}} = \frac{59333}{2500} \approx 24 \text{ pieces.}$$

Table 2

Main rated values of the photovoltaic module SP500M6-96

Characteristic	**Symbol**	**Value**
Electric characteristics		
Maximum capacity	P_{max}	500 W
Maximum voltage	U_{max}	48.63 V
Maximum current	I_{max}	10.28 A
No-load voltage	U_{NL}	58.95 V
Short-circuit current	I_{SC}	10.87 A
Efficiency of galvanic element	η_c	19.51%
Number of cells	n	96 pieces
Mechanical characteristics		
Weight	m	26 kg
Length	l	1956 mm
Width	b	1310 mm
Thickness	h	45 mm
Total area	S_1	2.56 m^2

Total area of the involved modules was $S_{\text{total area}} = S_1 \cdot N^{SE} = 307.2\ м^2$, i.e. in terms of 462.5 m^2 of the roof area of traction substation, that is equal to 66% of it. Moreover, there was the possibility to locate photomodules in the most favourable way having selected the distance between their rows using the formula:

$$L = l_{\text{mod}} \cdot \sin \frac{[180 - (\beta + \theta) \cdot \frac{\pi}{180}]}{\sin(\frac{\theta \cdot \pi}{180})}, \tag{1}$$

where l_{mod} is module length; β is inclination angle of a photomodule to the horizon; θ is angle of solar altitude.

The obtained distance was 1.37 m. Fig. 3 shows the layout design corresponding to its calculation.

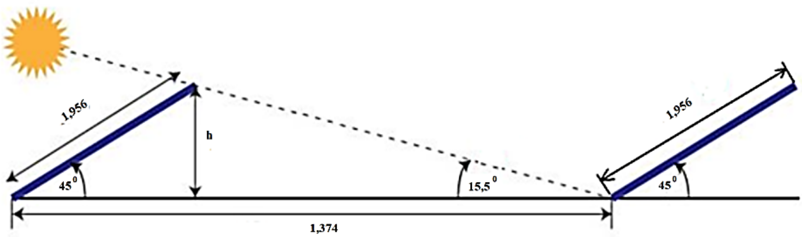

Fig. 3. Layout plan for the rows of photomodules on the traction substation roof

Basing on the dimensions of the traction substation roof (54.2×7.95m), the photomodules were arranged in three rows, each of 40 pieces, with the interval of 1.37m between them. Fig. 4. demonstrates a general view of the section of the photomodules arranged like that.

It is obvious that in winter, when the module capacity decreases considerably due to the low intensity of solar radiation and short daylight hours, electric energy generated by that SEPS will not be enough. To increase the SPES capacity, it is required to have not only considerable costs for additional modules but also additional areas to locate them.

In case of insufficient volumes of SEPS generation, automatic switch of the supply source disconnects it from the mains. In terms of the variant, for most of the year SCB power is supplied from the main source and much electric energy, generated by photomodules, is just lost.

Fig. 4. General view of the section of photovoltaic modules mounted on the roof, TS

Thus, the indicated RES implementation, being characteristic for the mains of non-traction energy consumers, cannot be considered as absolutely successful. In practice, it is implemented spontaneously without the available substantiated methodologies and recommendations.

3. Tools for experimental studies concerning the possibilities to use RES in the power supply systems for non-traction consumers

It is understood that to make decisions as for the use of some renewable energy source in the power supply systems for non-traction consumers it is required to have enough information for determining their technical and economic indices. Taking into account the random nature of input of energy resources, corresponding to the case, the specifications of equipment to be used should be either clarified or even identified independently. Thus, adequate experimental base should be available.

While orienting only to wind and solar radiation, analyze the possibilities of the development of experimental plants simulating the operation of corresponding equipment. Before doing that, it is necessary to study some information concerning the mentioned RES.

It is known that wind is formed as a result of nonuniform heating of the Earth’s surface by the sun. The air circulates as a result of its rotation around its axis as well. In this context, in the northern hemisphere it moves counterwise, while in the southern hemisphere it moves clockwise.

According to the expert estimation[15], Ukraine has great resources of wind energy which annual technical potential is almost 30 bln kW·h. Unfortunately, regional distribution of that resource is not uniform.

Depending on the generator capacity, the available wind plants are divided into the classes, which parameters are represented in Table 3. Nowadays, plants with horizontal axis (Fig. 2) are the most popular ones. Their main elements are as follows: wind-receiving device (blade), electric generator and reducer to transmit torque to it (located in a nacelle), and tower.

Table 3

Classification of wind power plants

Plant class	Capacity, kW	Wheel diameter, m	Number of blades	Purpose
Low capacity	15 – 50	3 – 10	3 – 2	Battery charging, power supply for pumps, household needs etc.
Medium capacity	100 – 600	25 – 44	3 – 2	Power generation
High capacity	1000 – 4000	> 45	2	Power generation

A wind-receiving device together with the reducer form so-called wind motor, which torque is generated owing to the specially selected blade configuration. It is clear that to use wind power plant (WPP) analyzed in the paper only low-capacity plants may be suitable (not more than 50 kW).

Gear set together with a wind turbine form so called wind engine which torque originates owing to specially selected configuration of blades. It is understood that only low power installations are acceptable for WPP, considered by the research (i.e. no more than 50 kW).

Experimental plant to study WPP, which scheme is represented in Fig. 6, includes following basic components: nacelle of the analyzed WPP; asynchronous motor driving the generator; frequency converter (FC) ПЧ-2000 which helps control AM rotating velocity simulating the wind flow action; continuous power supply source (CPSS) ДБЖ – 1.5/3С-ВГ which produces in output the stabilized constant and

[15] Індустрія вітроенергетики в Україні набирає оберти. URL : https://energytransition.in.ua/industriya-vitroenergetyky-v-ukrayini/

sinusoidal voltages with their digital indication; personal computer with software for corresponding processing of the obtained data and SCPS and FC matching; and storage battery with the voltage of 24 V.

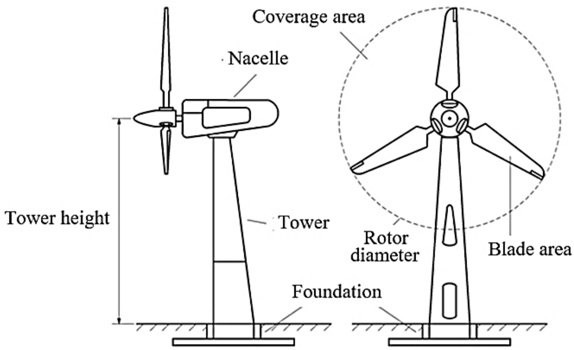

Fig. 5. Principle diagram of a wind power plant

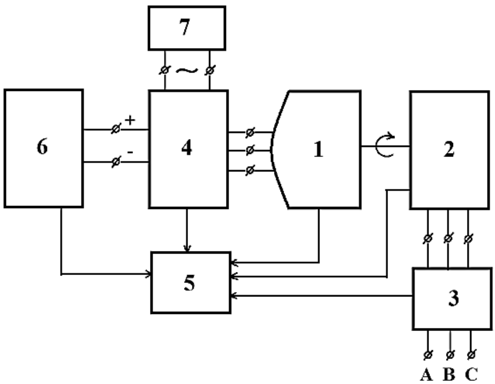

Fig. 6. Principle diagram of the experimental wind power plant:
1 – nacelle with generator; 2 – AM with belt drive; 3 – frequency converter (FC) ПЧ-2000; 4 – continuous power supply source (CPSS) ДБЖ – 1.5/3С-ВГ; 5 – personal computer; 6 – storage battery (SB); 7 – alternating current loading

In the process of analysis, following data are obtained and transferred to the PC for their processing: magnitude of currents in circuits of the generator and the one coming in the inverter; voltage value on the SB terminals;

degree of SB charge; temperature of FC radiator; state of regulator of the current entering from WPP; state of CPSS switches and voltage availability on CPSS; and rotating frequency of the generator shaft. Fig 7. shows general view of the developed experimental wind power plant.

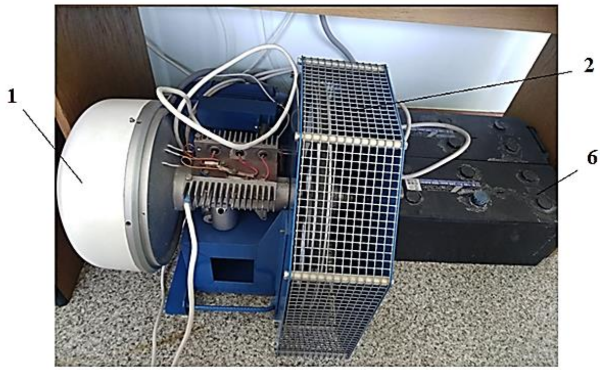

Fig. 7. General view of the experimental wind power plant:

1 – nacelle with generator; 2 – AM with belt drive; 3 – frequency converter (FC) ПЧ-2000; 4 – continuous power supply source (CPSS) БЖД– 1.5/3С-ВГ; 5 – personal computer; 6 – storage battery; 7 – alternating current loading

Moving on to the analysis of the experimental solar plant, it should be remembered that solar energy is converted into electric one mostly by direct photovoltaic conversion with the use of semiconducting elements. First, photovoltaic plants (PVP) were used as the power source for space equipment as it was the only way to provide electric energy for that kind of facilities. Thus, high specific cost of that production did not prevent from application of that technology.

Use of photovoltaic converters to generate great amount of electric energy on the Earth is still problematic not only due to its expensiveness but also due to the necessity to cover huge areas for their location. However, rational use of photovoltaic plants to supply power for the consumers being scattered over the large territories or located far from the centralized power grids, may be the only (in some cases) expedient way for their power supply.

Principle of the photovoltaic converter work is based on the phenomenon of internal photoeffect in semiconductors and effect of division of charge carriers (electrons, holes) by electron-hole transfer or potential barrier of the metal – dielectric – semiconductor (MDS) type. Nowadays, silicon is the most promising material for that use; it is characterized by high mobility of charge carriers, producibility, and sufficient amounts in the earth’s interior.

The simplest device to collect a lot of solar energy is a flat battery with many photo elements connected in the successive and parallel groups for reaching the required output capacity and voltage. Despite the fact that it differs with spectral selectivity, the battery does not react to the infrared band of spectrum which results in its considerable heating and distinct decrease in the conversion efficiency.

Experimental plant to study PVP is developed on the basis of the principle diagram represented in Fig. 8. It consists of solar panel 1, simulator of solar radiation 2, sensor of the radiation density 3, unit of energy conversions and accumulation of the necessary information 4, storage battery 5, and personal computer 6. During the study, following information is recorded and collected in unit 4: voltage on the photopanel output, $U_{f.p.}, V$; loading current of a photopanel, $I_{f.p.}, A$; radiation density $G, W/m^2$; and panel temperature $T_{f.p.}, {}^0C$.

Simulator of solar radiation is made in the form of a mobile panel with specially selected electric bulbs mounted on it; the bulb light is close to the one of solar spectrum (PHILIPS crypton bulbs). The simulator capacity may be varied by regulator; it also moves towards or backwards from the photovoltaic panel by means of a mechanical device.

Fig. 9. shows general view of the experimental plant based on the represented principle diagram.

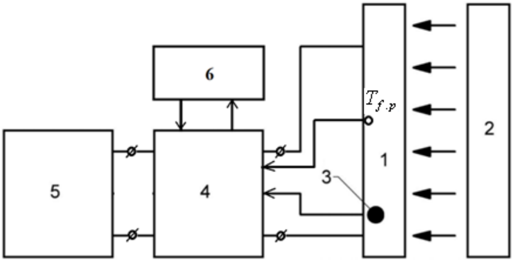

Fig. 8. Principle diagram of the experimental photovoltaic plant:
1 – solar electric panel; 2 – simulator of solar radiation; 3 – sensor of radiation flow density; 4 – unit of energy and information conversions; 5 – storage battery; 6 – PC

Finally, consider the equipment for studying wind flow or solar radiation intensity within the places of possible location of WPP or PVP. In terms of the first case, today there are a lot of compact converters used for construction, production, operating wind power plants – everywhere where it is necessary to record accurate meteorological data to meet the specified conditions. Our research involves compact sensor of wind velocity made by "Micro-Step-MIS" Ltd (Russia), which general view is given in Fig. 10.

The device is easy to mount on any available supports (posts, roofs of buildings etc.) after its raising at the required level by the additional pipe. It has following technical characteristics: measuring range is from 0.5 to 50 m/s; accuracy is $\pm 3\%$ of real value; dimensions are: 135×225 mm; and weight is 0.75 kg.

The obtained values of wind velocity are recorded and shown digitally. More details about the device can be found on the company site. The number of the product we use is 4.3518.00.700.

To measure solar radiation intensity, pyranometer SMP made by KIPP&ZONEN was used. The device is specially designed to record the solar energy flow falling on a flat surface from the sun and horizon within the wavelength range from 300 to 3000 nanometers (Nm). The device has intellectual interface; it is made in two modifications: with voltage analogue output (from 0 to 1 V) and with signal current (from 4 to 20 mA). We have used the first variant.

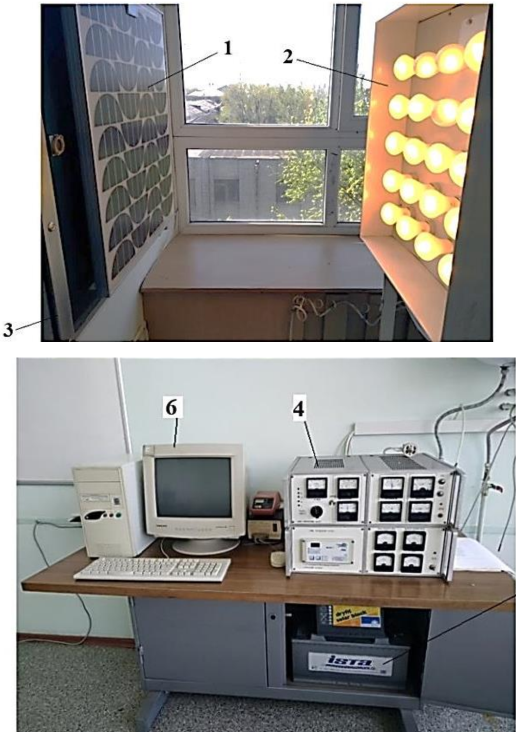

Fig. 9. General view of the experimental photovoltaic plant:
1 – photopanel; 2 – simulator of solar radiation; 3 – sensor of radiation flow density; 4 – unit of energy and information conversions; 5 – storage battery; 6 – PC

Fig. 10. General view of the applied device to measure wind velocity made by "Micro-Step-MIS" Ltd (Russia)

Fig. 11. demonstrates general view and scheme of signal passing in the pyranometer. It involves two-conductor successive interface RS-485. All the technical characteristics of the applied device as well as other modifications can be found on the site of company representative in Ukraine: http://data-luff.com, e-mail:luff@ukr.net.

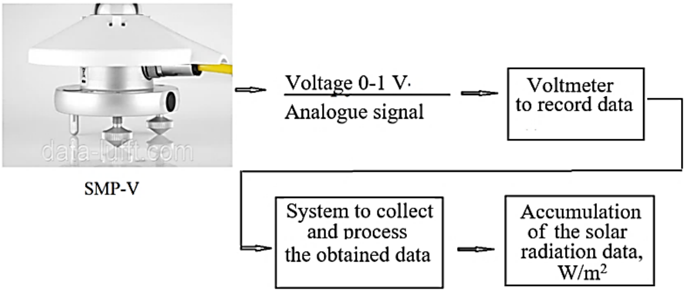

Fig. 11. General view and sequence of the information passing in the pyrometer SMP-V

4. Specifics of using wind power plants as the additional power supply sources in non-traction mains

While making decisions concerning RES application in the power supply systems for non-traction consumers of railway mains, first it is required to identify the way how to supply the generated power for the consumers. That is possible either in the separated (autonomous) mode for a specific loading share or to all the consumers immediately through the electric main.

It is rather difficult to state what variant is more expedient for the specific case due to the random nature of wind flows (which is the energy resource in this case) and additional uncertainty related to the features of the operation of wind power plants in different climatic conditions. These problems need detailed preliminary analysis during the concept design stage of such implementation. Efficient WPP use in the indicated mains requires knowing and considering all the features of that kind of generation.

Thus, before identifying the possibilities of providing non-traction consumers of electric mains with WPP power, consider the peculiarities of wind flows in some Ukrainian regions. Use the data of wind measuring in these regions obtained with the help of the aforementioned device. The measurements were carried out at the altitude of 50 m above the earth's surface and recorded with the interval of $\Delta t = 10$ min.

Fig. 12 represents distributions of the obtained velocities at the distance of 50 m further south than Zaporizhzhia and 50 m to the south from Dnipro near the restricted zone of Prydniprovska railway. We can see that in the first case the prevailing velocity is 5-6 m/s; in the second case, the prevailing velocity is 7-8 m/s. Winds of more than 15-20 m/s velocities at the specified altitude, being the most expedient one for medium-capacity WPP wind motors, are of low probability.

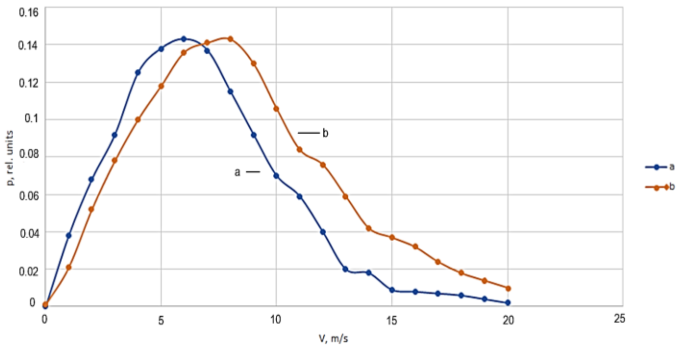

Fig. 12. Distribution of wind velocities near Vasylivka, Zaporizhzhia Oblast (a) and Novomoskovsk, Dnipropetrovsk Oblast (b) according to the results during 2018

The mentioned distributions are described with Weibull function with coefficients of altitude a=6.8612 and form b=2.4344 in the first case and a=7.6713 and b=2.6311 in the second case respectively. As for the features of wind velocity changes throughout a year, in terms of the indicated regions it is the same characterized by the dependence shown in Fig. 13.

The represented distribution shows that the wind velocity in May-August is almost three times lower than the one observed in Autumn-March. Consequently, while identifying the possibility of autonomous power supply for specific non-traction consumers at the expense of wind power plant energy, it is necessary to consider possible volume of its generation within the period from late spring to early autumn. It means that actually stronger winter winds will not be used at all.

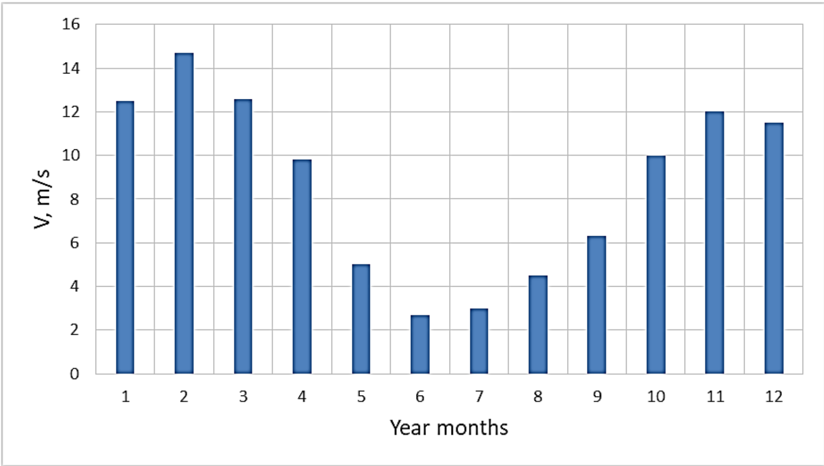

Fig. 13. Annual distribution of the monthly averaged wind velocity characteristic for the areas under consideration

Finally, identify the character of wind velocity distribution throughout a day. Fig. 14 shows the distribution in relative (to maximum) daily values averaged throughout a year and in terms of regions under consideration. We can see that within the indicated interval, wind velocity has clear gaps: from 7 till 11 a.m. and from 6 till 9 p.m. Thus, the share of electric energy generated by WPP within that period is much lower than at night when consumers do not need it so much; in terms of autonomous energy supply, that fact is rather important.

In this case, it is necessary to use buffer accumulation to store the available electric power. Although today we can do it in different ways, the most universal method is the use of storage batteries which will store extra energy and supply it when generation will not be enough. In other words, when such energy supply system is operating, SB will accumulate some share of electric power generated by RES, coordinating the stochastic nature of its generation with the consumption randomness.

It is obvious that in this case the energy generated by WPP will be distributed as follows:

$$E_{WPP} = E_{SC}^{WPP} + E_{Ch}^{SB}, \tag{2}$$

where E_{SC}^{WPP} is energy share consumed by the WPP loading; and E_{Ch}^{SB} is energy share coming in the SB during charging.

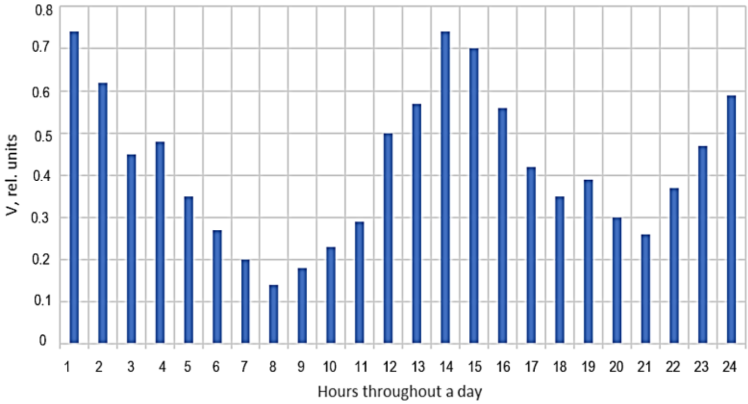

Fig. 14. Distributions of relative wind velocities throughout a day characteristic for the areas under consideration

In this context, general amount of electric energy consumed by the system loading will be as follows:

$$E_{SC} = E_{SC}^{WPP} + E_{In}^{SB}, \tag{3}$$

where E_{In}^{SB} is energy incoming from the SB to consumers.

Having transformed the equations (1) and (2) relative to E_{SC}^{WPP} and having compared the obtained results, we will have:

$$E_{WPP} = E_{SC} + E_{Ch}^{WPP} - E_{In}^{WPP}. \tag{4}$$

Thus, we find that energy share accumulated in SB is:

$$E_{SB} = E_{Ch}^{SB} - E_{In}^{SB}. \tag{5}$$

It is clear that the energy share accumulated in SB during charging will be equal to:

$$E_{Ch}^{SB} = U_{SB} \cdot I_{Ch}^{SB} \cdot \tau_{Ch} \cdot \eta_{Ch}^{SB}, \tag{6}$$

where U_{SB} is voltage on the SB terminals; I_{Ch}^{SB} is SB charging current; τ_{Ch} is charging period; η_{Ch}^{SB} is efficiency of SB charging.

In this context, following energy share will be taken from SB during the discharging:

$$E_{In}^{SB} = U_{SB} \cdot I_{In}^{SB} \cdot \tau_{In} \cdot \eta_{In}^{SB}, \tag{7}$$

where I_{In}^{SB} is SB discharge current;

τ_{In} is discharging period; and

η_{In}^{SB} is efficiency of SB discharging.

Thus, following accumulated energy share is left in the SB in case of its simultaneous charging and discharging:

$$E_{SB} = U_{SB} \cdot (I_{Ch}^{SB} - I_{In}^{SB}) \cdot \tau \cdot \eta_{SB}, \tag{8}$$

where η_{SB} is generalized SB efficiency; and

τ is duration of energy conversion in the SB.

At the same time, it is known that[16] the energy accumulated in the SB is determined by the value of voltage U_{SB} and nominal capacity of the battery:

$$E_{SB} = U_{SB} \cdot C_{SB}^{nom}. \tag{9}$$

Having compared the dependencies (8) and (9), it is understood that the required nominal capacity of buffer SB of that power supply system for non-traction consumers of railway mains should be defined as:

$$C_{SB}^{nom} = (I_{Ch}^{SB} - I_{In}^{SB}) \cdot \tau \cdot \eta_{SB}. \tag{10}$$

In this context, the used SB capacity at a specific moment will be equal to:

$$C = \eta_{SB} \int_0^{\tau} \left[i_{SB}^{3}(t) - i_{SB}^{p}(t) \right] \cdot \tau \cdot dt. \tag{11}$$

It is known that the efficiency of a total charging-discharging cycle, e.g. of lithium accumulation battery, is 0.8 ÷0.9[17]. The calculations performed to define η_{SB}=0.8, taking into account the randomness of the process of energy generation and consumption, have helped to determine the following: for the guaranteed energy supply of the loading with 60 kW·h daily needs, the SB should accumulate the energy amount of 104.5 kW·h. Consequently, total capacity required for that battery with the voltage of 12 V is:

$$C_{SB} = \frac{E_{SB}}{U_{SB}} = \frac{104500}{12} = 8708.33 \text{ A} \cdot \text{h}.$$

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[16] Будько В.І. Розроблення математичної моделі роботи автономної зарядної станції електромобілів від вітроелектричних установок. *Відновлювана енергетика*. 2017. № 3. С. 6–13.

[17] John Sun «Car Battery Efficiencies». URL : http://large.stanford.edu/courses/2010/ph240/sunl/.

It is clear that here we need the accumulators designed for much higher voltage, e.g. traction lead-acid ones with the voltage of 120 V.

Thus, the energy, accumulated in the storage battery should exceed the amount necessary for consumption by about 1.7 times. Following calculations have made it possible to define that in terms of further increase in energy consumption, values of that so-called reserve coefficient of SB experience no changes; the value may be recommended for practical use.

Ultimately, consider operational features of WPP which will influence their efficiency in the power supply systems of non-traction consumers. First of all, capacity of any wind power plant is limited by a certain so-called nominal value P_n regardless of wind power. Thus, Fig. 15 exemplifies the dependence of WPP characteristic upon wind power for Chinese installation ZH5KW which rated capacity is 5kW[18].

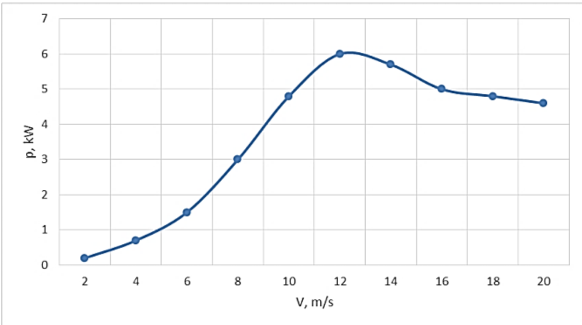

Fig. 15. Dependence of WPP capacity of ZH5KW type upon the wind speed

Taking into consideration the fact that each wind turbine has its own so-called critical wind speed V_{cr}, achieving which it stops[19], WPP model may be set as follows:

$$P_{WPP} = \begin{cases} 0, \ if \ V \le V_0 \ i \ V \ge V_{cr} \\ f(V), \ if \ V_0 < V < V_N, \\ P_n, \ if \ V_N < V < V_{cr} \end{cases} \quad (12)$$

where V_0 is initial wind speed required for the WPP operation, m/s; and

[18] URL : http://byd.iproaction.coni/ua/vehicle/e6.htm.

[19] Diaf S., Belhamel M, Haddadi M., Louche A., A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy,* Volume 35. Issue 11, pp. 5708-5718, 2007.

V_N is nominal wind speed, m/s.

In this context, $P_{WPP} = f(V)$ function used to identify WPP capacity in terms of the specified wind speed within $V_0 < V < V_N$ interval may be determined on the expression[20]

$$P_{WPP}(V) = \frac{1}{2}\rho \cdot V^3 \cdot F \cdot \eta(V) \cdot \eta_{WPP}, \qquad (13)$$

where ρ is wind flow density, kg/m^3; $\eta(V)$ is coefficient of the wind flow use; F is rotor swept area, m^2; η_{WPP} is the generalized WPP efficiency.

Generally, rotor swept area is calculated as a circular area

$$F = \frac{\pi \cdot d^2}{4}, \qquad (14)$$

where d is diameter of the wind turbine.

In terms of 760 mm hg atmospheric pressure and 15°C temperature, wind flow ρ is 1.225 kg/m^3.

Fig. 16 shows the simplified dependence of the mentioned WPP upon the wind speed corresponding to expression (12) and using generally for calculations.

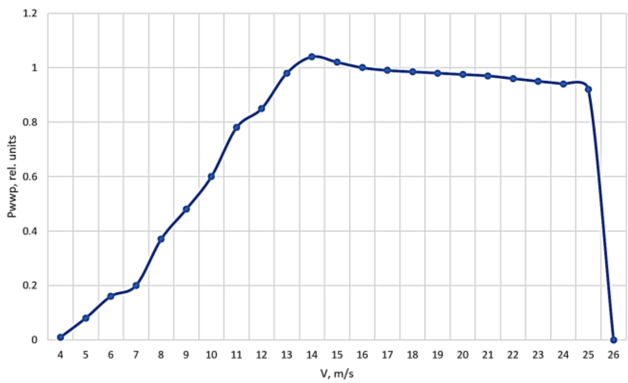

Fig. 16. Simplified analytical dependence of WPP capacity of ZH5KW type upon the wind flow speed

[20] Кудря С.О., Будько В.І. Вступ до спеціальності. Нетрадиційні та відновлювані джерела енергії: Електронний курс лекцій. Київ : Національний технічний університет України («КПІ»). 2013. 360 с.

If one compares distribution of wind speeds in the analyzed districts of Zaporizhzhia and Dnipropetrovsk Oblasts (see Fig. 12) with the capacity dependence of the mentioned WPP type (Fig. 16), it becomes understood that it is not expedient to apply such an installation. The matter is that $V_H \div V_{кр}$ interval, being the most efficient for it, falls on improbable for the areas with $14 \div 20$ m/s wind speed. It is obvious that WPP with no more than 12 m/s critical wind speed V_{cr} should be applied in this case.

All this suggests that to generate the required electric energy amount irrespective of a season, the wind turbine should involve several installations with small value of critical speed rather than one more powerful WPP which would resist all possible windings being typical for the terrain. Krasnodon WPS can support the idea since it involves ten different installations of FL 2500 type[21]. Fig. 17 demonstrates its annual electric energy generation[22].

The dependence explains that the WPS generates more energy in summer to compare with winter when it is more needed. Moreover, the terrain is characterized by rather strong winds. Thus, the power station does not use the available resource in full.

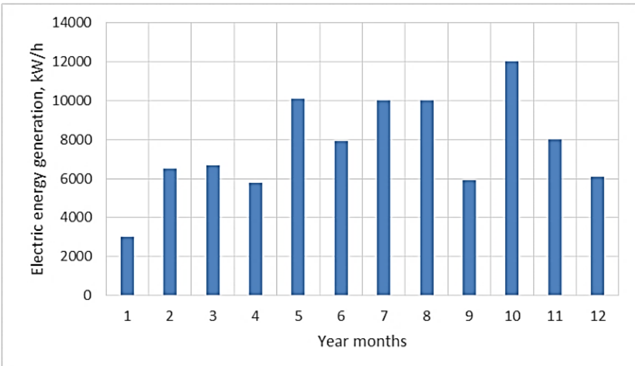

Fig. 17. Dynamics of the electric energy generation by Krasnodon WPS in 2018

[21] Портал відкритих даних. URL : http://data.gov.ua.

[22] Будько В.І. Автономні енерговузли на основі відновлюваних джерел енергії з різними системами акумулювання енергії. *Відновлювана енергетика*. 2015. № 2. С. 21–25.

If electric power sources are developed by powerful WPPs, which critical speed rather high as for the winds in the areas of their location, then it will result in the decreased efficiency of the installation as well as in the necessity to have more consumers who need the excess of the generated electric energy. It means that they have to work for the shared mains rather than operating autonomously.

Hence, if wind plants are used in power supply networks of non-traction consumers of railway mains, it is more expedient to connect them directly to the networks and consume the whole energy, generated by them, while decreasing its consumption by the value from the mentioned electric power supply system. In this context, it is possible to improve efficiency of the extra generation sources by means of introduction of different types of wind turbines which would provide simultaneously maximum coefficient of their annual use and take into consideration the features of wind speed distribution within a specific area (i.e. apply maximally the available energy resource). The problem should be considered as a separate optimization task while designing such energy sources.

5. Features to use photovoltaic plants as extra energy sources within non-traction mains

In each specific case, efficiency of PVP use in the power supply systems of non-traction consumers is identified by means of climatic and meteorological conditions of the area where they are planned to be mounted. Hence, PV plants should follow after previous energy evaluation of solar radiation which helps support expediency of such an extra source.

Solar radiation intensity, which defines energy amount falling on a measurement unit of land surface area for a single time period, is of random nature like wind flow energy. Thus, the electric energy, generated by photovoltaic plants at any time is of unpredictable amount too.

Like in case with WPP, capacity of photovoltaic battery (PVB) is limited by a specific value, so-called nominal (rated) capacity P_{nom}^{FVB} which remains constant after solar radiation intensity achieves its nominal values. To support the fact, Fig. 18 demonstrates the experimental dependences of a photomodule capacity upon the mentioned intensity in terms of voltage invariance on its clamps.

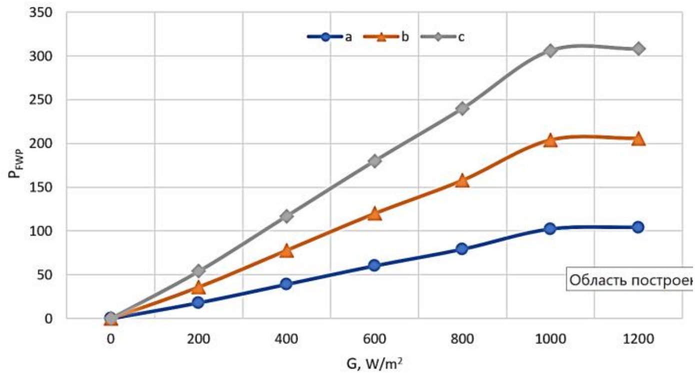

Fig. 18. Experimental dependences of the photomodule capacity dependence upon the solar radiation intensity when voltage on clamps is 12V (a), 24V (b), and 36V (c)

Paper[23] determines a dependence of photovoltaic battery capacity within $0 \div G_{nom}$ interval using the equation

$$P_{FVP} = \eta_{FVP} \cdot F_{FVP} \cdot G_t = \eta_n \cdot \eta_{CU} \cdot [1 - \beta \cdot (T_C - T_{RT})] \cdot A_{FVP} \cdot G_t, \quad (15)$$

where G is solar radiation intensity, W/m^2;

η_{FVP} is battery efficiency factor;

η_n is rated photomodule efficiency;

η_{CU} is capacity use efficiency;

β is temperature efficiency coefficient;

T_{RT} is the rated temperature of photocells, ^{0}C; and

T_C is the current photocell temperature, ^{0}C.

The latter is identified as follows:

$$T_C = T_{AT} \cdot (\frac{T_{nom}}{800}) \cdot G_\tau, \quad (16)$$

where T_{AT} is ambient temperature, ^{0}C; and

T_{nom} is nominal photocell temperature, ^{0}C.

Efficiency of the use of capacity, when it achieves the last maximum value, is $\eta_{CU} = 1$. As for the temperature efficiency coefficient, it is

[23] Кудря С.О. Нетрадиційні та відновлювані джерела енергії : підручник. Київ : НТУУ «КПІ», 2012. 492 с.

considered as the virtually unchanged one for the specific semiconductor type. For instance, it is $\beta = 0.004 \div 0.006\ ^0C^{-1}$ for silicon photocells.

Taking into consideration the fact that η_{CU}, β, T_{nom} *and* F_{FVP} are technical parameters of PVP, specified by their manufacturer, temperature and solar radiation intensity remain independent random values in terms of equation (15). The abovementioned verifies linear nature of the obtained dependences of the output capacity upon intensity of the latter within $G = 200 \div 1000\,\text{W/m}^2$ interval.

Advantages of model (15) are as follows: it takes into consideration influence of environmental temperature and photomodule temperature making it possible to simulate PVB-based generating stations. However, it cannot demonstrate dependence of the plant capacity upon the voltage on its clamps, and intensity of current consumption despite the fact that the last ones are among the key parameters of any photovoltaic panel.

Thus, solution of relevant practical problems more often applies a dependence, although simplified one, named as a model of ideal photocell[24]. It corresponds to the most popular and easy to implement one-diode photocell replacement circuit (Fig. 19) consisting of photocurrent source (I_{FC}), diode (D), shunt resistor (R_{Sh}), and resistor simulating internal series cell resistance (R_{ISR}).

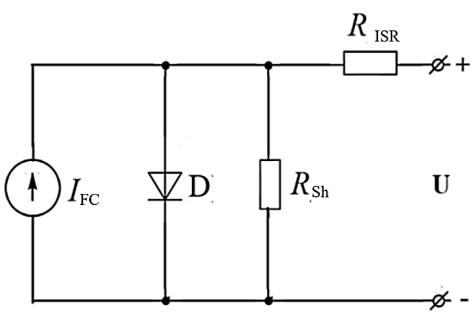

Fig. 19. Equivalent circuit of a photocell replacement

[24] Wasynczuk O., Dynamic behavior of a class of photovoltaic power systems. IEEE Transactions on Power Apparatus and Systems 102 (1983) 3031-3037.

Phang J.C.H., Chan D.S.H., Philips J.R. Accurate analytical method for the extraction of solar cell model parameters J.C.H. Phang, D.S.H. Chan, J.R. Philips Electronics Letters 20 (1984) 406-408.

The mentioned, more widely used dependence of a photocell capacity is

$$P_{FVB} = U_{FVB}\{G\cdot[I_{SC} + K_I\cdot(T - T_{RT})] - I_D\cdot(\exp\frac{q\cdot U_{FVB}}{K\cdot T\cdot A}) - I\}, \quad (17)$$

where U_{FVB} is voltage across a photocell, B; I_{SC} is short circuit current of a photocell, A; K_I is temperature coefficient of short circuit current; T is operating temperature of a photocell, ^{0}K; T_{RT} is rated temperature of photocells, ^{0}K; I_D is reverse saturation current of a diode, A; $q = 1.6\cdot10^{-19}$ Coulomb is electron charge; $K = 1.38\cdot10^{-23}$ J/^{0}K is Boltzmann constant; A is coefficient of the photocell ideality determined by means of its manufacturing method; I is current consumed, A.

Despite the fact that the equivalent models and (17) dependence are considered as the ideal one, they should be related to a load value and nature to evaluate the photocell influence on the operation of the whole energy power supply system. That will make it possible to calculate the amount of the generated electric energy and evaluate efficiency of its use.

It is possible to identify the amount of electric energy, generated by means of photovoltaic conversion, with (17) dependence using the expression

$$W_{FVP} = \tau_{FVP}\cdot U_{FVP}\{G\cdot[I_{SC} + K_I\cdot(T - T_{RT})] - I_D\cdot(\exp\frac{q\cdot U_{FVB}}{K\cdot T\cdot A}) - I\}, \quad (18)$$

where τ_{FVP} is period of photovoltaic device operation, hours.

The equation describes a process of electric energy generation by means of a photovoltaic device under the specific conditions: solar radiation intensity (G), photocell temperature (T), and period of solar energy transformation into electric one (τ_{FVP}).

Identify the intensity nature of solar intensity relying upon the meteorological observation data of 2018. They were recorded with the help of a sensor, mentioned in Chapter 3, in the town of Vasylivka, Zaporizhzhia Oblast, with $\Delta t = 10$ min interval. The total amount of values is almost 25000. It has been determined that in terms of the terrain, length of day varies from 7 hours in December to 15 hours in June, i.e. 3.5 and 7.5 hours respectively on either side relative to the current value being 11.5 hours.

During the mentioned year, minimum solar radiation intensity was 400 W/m^2, and maximum value was 1000 W/m^2. In this context, if intensity fluctuations are considered within 8-10% from the last value, then such its value is available during April-August. Unfortunately, it depends heavily upon cloudiness, and may decrease down to the same 400 W/m^2 or even less. Fig. 20 demonstrates fragments of the fluctuations.

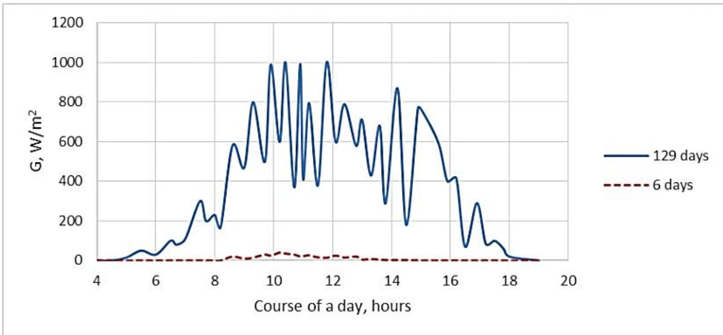

Fig. 20. Intake of solar radiation during a day in May (a) and a day in January (b) in 2018 (town of Vasylivka, Zaporizhzhia Oblast)

Thus, cloudiness complicates considerably electric energy generation by FVP. The matter is that average daily intensity may experience more than twofold decrease from 1000 W/m^2 on sunny days down to the same 400 W/m^2. As for the distribution of the experimental data being considered, their histogram (Fig. 21) stores almost constant $300 \div 900$ W/m^2 intensity value.

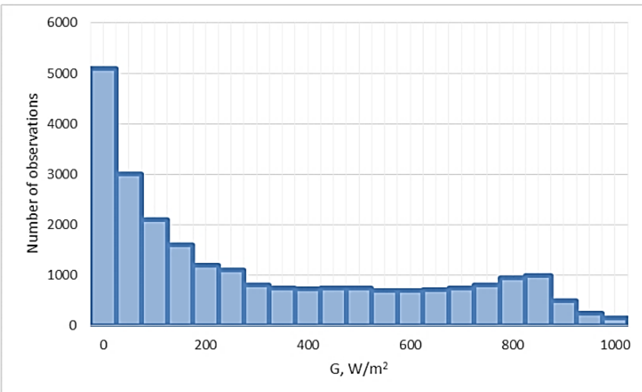

Fig. 21. Histogram of experimental data distribution as for the solar intensity distribution in 2018 (town of Vasylivka, Zaporizhzhia Region)

The analysis supports the idea that while using PVP as the autonomous supply source of the specific non-traction consumers (i.e. their disconnection from the mains), it is required to select capacity of a photovoltaic station in terms of the solar radiation intensity in November-January. In this context, summer will demonstrate significant excess of the generated electricity which should be lost or used in some way. Like in the case with WPP application, a buffer SB has to be available. The battery will smooth out fluctuations in energy generation or even its lack at night, within 24 hours.

As it has been determined in the previous chapter, the energy, accumulated by SB, excess in the amount of daily consumption should be more than 1.7 times. Consequently, 60 kW·h consumption should involve such storage battery which can accumulate 104 kW·h of electric energy. For instance, if voltage is 12V, its energy intensity should be 8708 33 A·h.

It is also important to bear in mind that it is possible to charge the SB (as it is known by[25]) if only output capacity of a power source, being PVS in this case, is more than the mentioned 12 V. That is why, selection of the type of photopanels, their amount, and connection diagrams should involve the nuances as well.

Consider use of photovoltaic panel of PV- MLV 250 HC type which specifications are listed in Table 4[26]. Dependences of output voltage of the photovoltaic panel upon the solar radiation intensity, obtained with the help of the abovementioned experimental setup, are in Fig. 22.

In terms of the considered example, the last conditions will be met since output PVS voltage is not less than 12 V required for SB. Hence, at radiation intensity, corresponding to April-August (almost 1000 W/m^2) when output voltage of the panels is 31 V it will become possible to connect in series no more than two storage batteries. That is quite sufficient even in winter since in terms of 29 V voltage of one panel the mentioned number of batteries will provide the total 24 V value.

[25] Кудря С.О. Підвищення ефективності акумулювання енергії вітру в автономних системах. *Відновлювана енергетика*. 2009. № 2. С. 25–31.

[26] Photovoltaic Modules. URL : https://www.mitsubishielectricsolar.com/iiTiages/uploadsdocuments/specs/MLU_spec sheet 250W 255W.pdf.

Table 4

Specifications of photovoltaic panel of PV- MLU250HC [130] type

	Parameter	Value
1	Cell type	Monocrystalline silicon
2	Cell dimensions, mm	78×156
3	Number of cells within one panel, pieces	120
4	Maximum capacity, W	250
5	Guaranteed minimum value of maximum power, W	242.5
6	Idle voltage, V	37.6
7	Short circuit current, A	8.79
8	Voltage in terms of maximum capacity, V	31
9	Current in terms of maximum capacity, A	8.08
10	Efficiency, %	15.1
11	Tolerable deviations of maximum capacity, %	±3
12	Normal operating cell temperature, °C	45.7
13	Maximum voltage of the system, V	600
14	Cut out current, A	15
15	Overall dimensions, mm	1625×1019×46
16	Weight, kg	20

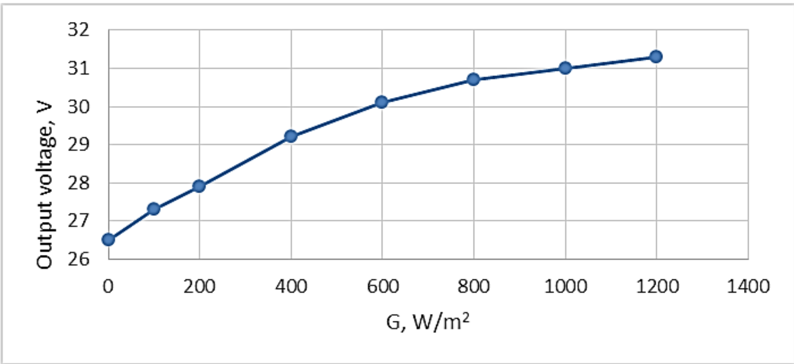

Fig. 22. Dependence of the output voltage of PV-MLU250HC photovoltaic panel upon solar radiation intensity

As for the total number of PV panels within a photovoltaic station, required to supply consumer with 60 kW capacity in summer, it is quite understood that in terms of 235 W (Fig. 23) by one panel, there will be necessary to connect in parallel 255 pieces. In winter, when unit capacity of PV panel drops down to 75 W, the station should involve 800 mentioned panels.

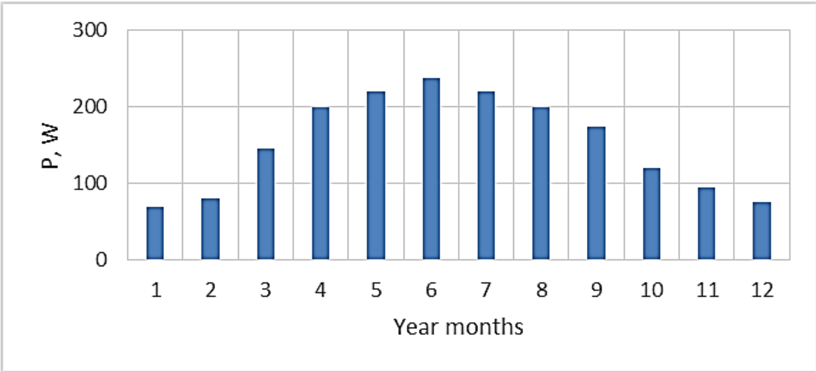

Fig. 23. Distribution of the average monthly capacity of PV panel of PV-MLU250HC type located in town of Vasylivka, Zaporizhzhia Oblast during 2018

6. Determining expedient way to use wind-power and photovoltaic installations within the supply systems for non-traction consumers

Use of renewable energy sources within the supply systems for non-traction consumers of railway mains has proper significant features which should be taken into consideration while making relevant decisions. The key feature is as follows: such consumers connect the mains since they are far from other electric power supply networks. Hence, it will be impossible to sell the excess of the generated energy.

Much electricity will be lost even despite the fact that the guaranteed power supply of consumers, being considered, requires that the capacity of corresponding generating plants should be increased significantly under the conditions of random nature of a wind flow of solar radiation intensity. Hence, in such a case both capital costs and operational costs may increase considerably making the implementation economically impractical.

Consider some possible alternatives to use renewable energy sources in terms of the mode. First of all, determine expedience of such, in fact autonomous, application of WPPs in the context of Ukrainian regions, considered before. Making use of the dependence of a wind turbine of

ZH5KW type upon the wind speed (Fig. 15) and averaged over the month annual distribution of the latter in the neighbourhood of Zaporizhzhia (Fig. 13), obtain indices of electric capacity of the plant for a year (Fig. 24).

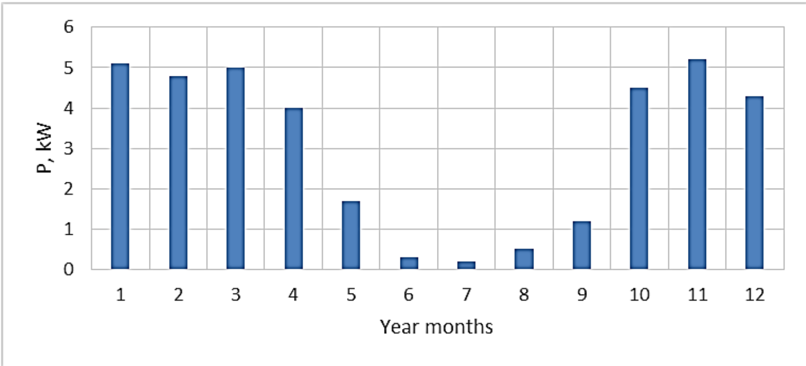

Fig. 24. Distribution of the annual electric capacity by WPP of ZH5KW type during a year in terms of its use in the neighbourhood of town of Vasylivka, Zaporizhzhia Oblast

The obtained dependence explains that in summer WPP capacity experiences almost 25 times decrease to compare with the winter season. Thus, to provide the required capacity of such an extra source (for instance, 60 kW), 12 turbines are needed in winter and 300 ones are needed in summer. It is understood that construction of WPPs with such number of facilities, being unnecessary during the most favourable season, is a bad idea.

It goes without saying that the situation may be improved while using facilities of different types for the WPPs. Some of them will have low critical wind speed to operate in summer with greater efficiency. They will be often disconnected in winter and energy will be generated by more powerful WPPs meant for winds being of maximum force within the area.

Chapter 4 considers an example of Krasnodon wind power plant constructed in such a way. However, operation in almost autonomous mode with no possibility to sell the excess of electricity in the energy market according to so-called “green” tariff is hardly expedient as well as the WPP use as a source for non-traction consumers of railway mains.

Then independent use of wind turbines for the needs in the context of the considered Ukrainian regions may be regarded as impractical.

The possibility to apply photovoltaic plants looks much better. If one pays attention to the electric power distribution by PVPs of PV-MLU250HC type, generated as it has been described in Fig. 25, it becomes obvious that it is only 3-4 times greater than in winter. Consequently, capital costs and operational costs will not be so heavy in November-February to compare with May-August if the number of PVPs is used to generate the required amount of electric energy.

However, use of photovoltaic plants will result in triple-quadruple excess of the electricity generated specifically in summer. Thus, such huge amount of electricity will be lost. It is inacceptable from the economic viewpoint even if loss, resulting from noisy electricity within traction railway mains, to which non-traction consumers under consideration are connected, is taken into account.

It is interesting fact that the most favourable seasons as for the use of wind and photovoltaic facilities do not coincide. Actually, they are opposite: when WPPs are of the maximum capacity, solar panels demonstrate minimum value and vice versa. Hence, it is worth considering an alternative of the combined use of such renewable energy sources.

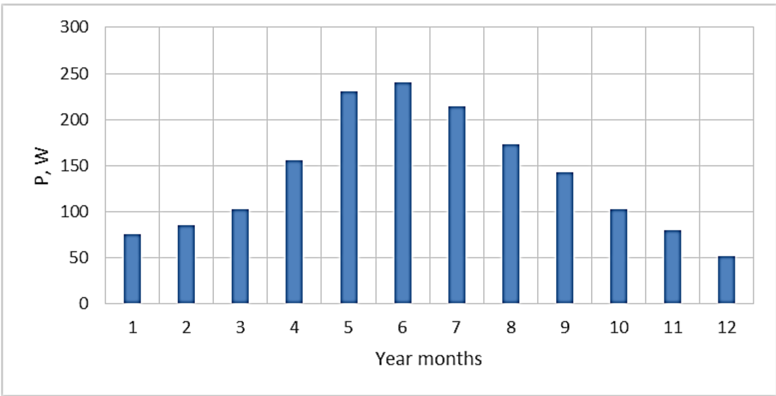

Fig. 25. Annual electric power distribution by PVPs of PV-MLU250HC type in the neighbourhood of town of Vasylivka, Zaporizhzhia Oblast

If the goal is set to construct such autonomous electric power station with similar 60 kW capacity generated by wind turbines in winter, then it will require 12 pieces of them. Fig. 26 (a) demonstrates annual distribution of the total average monthly capacity of the WPPs located within the territory.

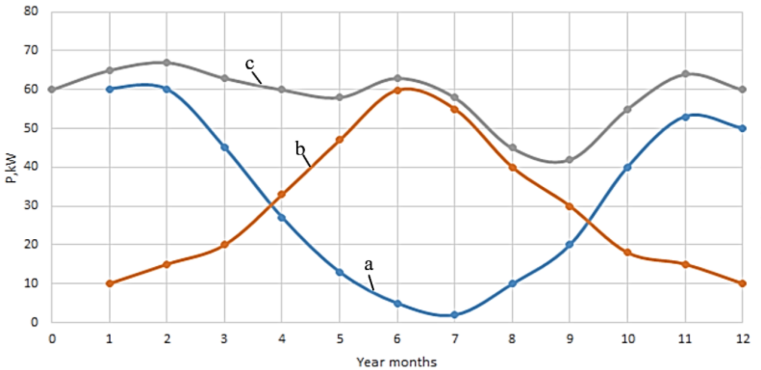

Fig. 26. Annual power distribution of wind (a), solar (b), and combined (c) generating capacities if they are constructed in the neighbourhood of town of Vasylivka, Zaporizhzhia Oblast

To cover the capacity by means of solar panels of PV-MLU250HC type in summer, they will be required 255 pieces in total. Fig. 26 (b) also demonstrates annual distribution of the total average monthly capacity by PVP. As a result of the combined use of WPP and PVP, being minimal for the case, annual capacity distribution of the power plant will look like in Fig 26 (c).

In this context, minimum excess of the generated electric energy will be available (i.e. almost 10%) in late winter-in early spring, and its deficit in the late summer-in the late autumn (i.e. no more than 25%). It is understood that the fluctuations of electricity generation amounts may be reduced drastically by means of complete elimination of the 25% while using reasonably different types of wind turbines as it has been mentioned or with the help of minor quantity increase of one or another supply source relying upon economic considerations.

7. Comparing economic attractiveness of alternative RES use within the supply systems for non-traction consumers

Previous Chapter considered three possible alternatives to use RES within the supply systems for non-traction consumers. It has been determined that their guaranteed 60 kW/h power supply will need: to apply only wind turbines (since their capacity is 5 kW, the number should be 300 pieces); to install only solar modules (since their capacity is 250 W, the number should be 800 pieces); and use simultaneously 12 wind turbines and 225 photovoltaic modules of the mentioned capacities. Fig. 27 demonstrates schematic diagrams of the proposed power supply alternatives.

As the diagrams explain, the system will use almost similar controllers, power converters, storage batteries, and switches in addition to supply sources. It is understood that a hybrid alternative can use multipurpose controllers with power converter functions both for wind turbines and for solar plants[27]. However, their current price still exceeds the total cost of the components taken separately. Hence, to define relative economic attractiveness of the proposed alternatives, it is quite sufficient to compare expenditures connected with the purchase of wind turbines and solar photovoltaic modules in one case or another.

Tables 5 and 6 demonstrate technical and economic indicators of the most popular home-produced solar photovoltaic modules and wind turbines being of the mentioned capacities. It is obvious that if a tender to purchase the equipment is held then solar photovoltaic modules Solar KD– 250P by EKO-ST Company (Ukraine) at the cost of UAH 5400 per unit and wind turbines Euro–Wind–5 by Eko–Raduga ltd at the cost of UAH 125.000 per unit would be used.

Relying upon the abovementioned, cost of the power stations in terms of alternative one of WPP implementation would be UAH 37500 thousand under the conditions of nonavailability of electric energy by traction mains. The price would be UAH 4320 thousand in terms of alternative two. If the combined alternative is used (i.e. when the number of wind turbines and solar photovoltaic modules is quite less to compare with the previous cases) then the total cost of the required quantity is UAH 2877 thousand only.

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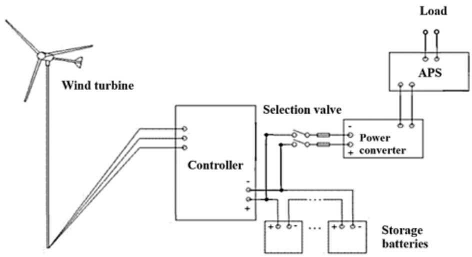
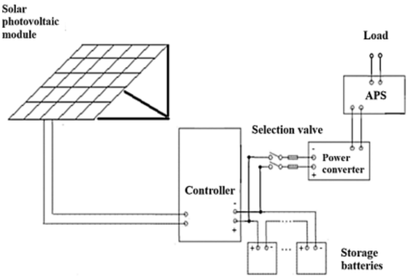
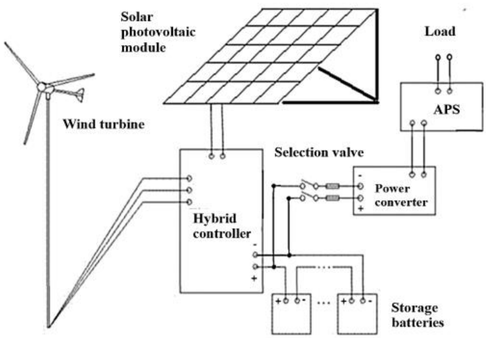
[27] Лежнюк П.Д., Рубаненко О.Є., Гунько І.О. Вплив інверторів СЕС на показники якості електричної енергії в ЛЕС. *Вісник Хмельницького національного університету*. 2015. № 2(223). С. 134–145.



a)



b)



c)

Fig. 27. Schematic diagrams of wind (a), solar (b), and combined (c) electric power supply systems. APS is automated power switch for the power source

Table 5

Technical-and-economic indicators of solar photovoltaic modules by *EKO-CT* Company (Ukraine, eco.st.lv@gmail.com)

Model	Nominal capacity, W	Nominal voltage, V	Voltage x. x., V	Price, UAH
KVAZAR KV 250P	250	30.7	37.3	10500
ALTEK ACS-250D	250	31.4	37.2	8100
SOLAR KD-250P	250	30.8	37.43	5400

Consequently, the use of wind turbines only is the worst alternative from the economic viewpoint; moreover, it is almost unacceptable. The combined alternative is the cheapest one; however, it is still too expensive to be implemented. It is understood that traditional supply sources should also be applied in the case. Nevertheless, the problem concerning the ratio between electric power supply using them and RES, and how the mains of non-traction consumers should be constructed needs further consideration.

Table 6

Technical and economic indicators of the current WPP

Manufacturer	Model	Capa-city, kW	Volta ge, V	Wind speed, m/s		Tower, m	Price, UAH thous.
				Ini-tial	rated		
MikroART ltd, Ukraine Vetrogenerator .ru	5/7 KW-480 LOW WIND	5 7 (max)	48	3	8	12	215
	FDV-5KW	5 7 (max)	48	2,5	10	8	549
Energo-Star ltd, Ukraine www.energostar.com.ua	Euro Wind 5	5 7 (max)	240	2	8	12	330
Eko–Raduga ltd, Ukraine www.ecoraduga.com	Euro–Wind–5	6 7 (max)	240	2,5	12	12	125
ALTAL GrupSrl, Moldova http://www.altalgrup.com	ALTAL – 5	5 6 (max)	240	2	10	12	170

CONCLUSIONS

The carried out research and studies help conclude the following:

1. Noisy energy for non-traction consumers supplied by railway mains on the one hand and their significant distancing from general power supply networks on the other hand make it attract other acceptable now autonomous power supply systems. They are diesel generators, petrol generators, and renewable energy sources.

2. Diesel and petrol electric facilities have a number of the mentioned advantages. However, their manoeuvrability, being the most important among the pluses, is neutralized by the fact that they are significant pollutants running on expensive fuel. Hence, even significant increase in electricity tariffs will not make them cost-effective.

3. Unfortunately, single cases of RES introduction in electric power supply for non-traction consumers are not of the integrated nature. Moreover, they are not based upon the specific reasonable measures.

4. At the same time, it is almost impossible to implement stimulating so-called “green tariff”, using electricity generated by RES, for electric power supply systems for non-traction consumers while selling its excess to the mains. On the other hand, it is still too expensive measure to use them to generate such electric energy amounts which would be sufficient for the guaranteed power supply of loads.

5. The experimental plants, designed for the integrated analysis of use of wind sources and solar sources within the power supply systems for non-traction consumers are of multipurpose nature. Moreover, they make it possible to specify the required values and dependences as for their engineering and power parameters to make correct decisions.

6. Taking into consideration the determined features of wind speed distribution in terms of seasons and day part in South-Eastern Ukraine for the guaranteed power supply for consumers by autonomous wind power plants, the latter should be equipped by different types of wind turbines to use the wind flow potential. In this context, their capacities and number should be selected relying upon a separate economic-based optimization task.

7. Taking into consideration the features of the analyzed RES-based electric power supply systems, they cannot be regarded as the autonomous alternative both in terms of autonomous and the combined variant. Substantiation of their expedient use as a part of electric power supply systems of the combined type needs specific attention.

8. Minimum and maximum solar radiation intensity has been identified within the mentioned Ukrainian regions in terms of seasons. The values are almost 400 W/m^2 and 1000 W/m^2 respectively. Unfortunately, they depend heavily upon the cloudiness thus decreasing even during a summer day down to a winter 400 W/m^2 value. The fact complicates considerably the electricity generation by PVP.

9. The research results support the idea that in the context of the considered territory, RES capacity experiences its 25-time summer decrease to compare with the winter season. As for the PVP, the situation is vice versa: December-February demonstrate decrease in capacity to compare with summer. However, it is only 3-4 times decrease.

10. Common use of minimum quantities of WPP and PVP within the systems of electric power supply for non-traction consumers results in the significant annual fluctuation of their total capacity. Moreover, they have either excess or deficiency being almost 20% of the required value. In this context, it is possible to reduce such fluctuations or even eliminate them by means of reasonable substantiation of the number of power plants and their types relying upon the mentioned optimization task.

11. To guarantee power supply of non-traction consumers during 24 hours, the electricity, generated by the autonomous wind turbines and solar power plants, should be accumulated in the amounts, 1.7 times exceeding the amount corresponding to load.

12. Implementation of such accumulation systems with the mentioned electricity amount based upon storage batteries increases significantly capital expenditures, connected with the autonomous power plant introduction, making its implementation economically unattractive.

13. Cost comparison of the required quantity of supply sources in terms of wind, solar, and the combined electric power stations proves the latter as the cheapest one. However, it may be economically inexpedient even without consideration of the required extra expenditures, connected with storage battery purchase, if it cannot sell the generated electricity on the “green” tariff.

14. RES use to supply power for non-traction consumers of railway mains should be implemented in terms of the alternative, closest to the combined one, while attracting traditional supply source of traction loads. Nevertheless, the problem concerning the ratio between electric power supply using them and RES, and what kind of the mains it should be to improve electric energy quality needs further consideration.

SUMMARY

The мonograph section is devoted to the urgent problem of implantation renewable energy sources into the power supply system of non-traction railway consumers. The use of additional renewable energy sources to power non-traction consumers minimizes the cost of electricity.

The authors consider issues related to the possibility of using additional generation of electricity in the power supply systems of railway transport through the use of wind turbines and photovoltaic stations, including for non-traction consumers. The analysis of wind flow features in some regions of Ukraine was carried out, and the measurement of wind speed in Zaporizhia and Dnipropetrovsk regions was obtained with the help of a compact wind speed sensor manufactured by Micro-Step-MIS LLC (Russia).

The nature of the intensity of solar radiation was clarified due to meteorological observations for 2018, recorded using a SMIR pyranometer from KIRP & ZONEN, which is specially designed to record the flow of solar energy falling on a flat surface from the sun and sky in the wavelength range from 300 to 3000 nanometers (Nm), which has an intelligent interface, in the city of Vasylivka, Zaporizhia region with an interval of minutes.

The originality is that the use of renewable energy sources in the power supply systems of non-traction consumers of railway transport, in particular photovoltaic installations and wind turbines, is proposed.

REFERENCES

1. Vijay D. (2013) Solar energy: Trends and enabling technologies [Text]. *Renewable and Sustainable Energy Reviews* / vol. 19, pp. 555–564.

2. Ryoichi K. (2014) Assessment of massive integration of photovoltaic system considering rechargeable battery in Japan with high time resolution optimal power generation mix model [Text]. *Energy Policy* / vol. 66, pp. 73–89.

3. Takaki K. (2014) Demonstration Experiment for Energy Storage and Rapid Charge System for the Solar Light Rail [Text]. *Energy Procedia* / vol. 57, pp. 906–915.

4. Сиченко В.Г., Бондар О.І., Прихода М.С. Аналіз впливу сонячної генерації на роботу тягових підстанцій електрифікованих

залізниць. *Світлотехніка та електроенерге*тика. 2015, № 1(41). С. 10–17.

5. Коновалова А.А. Потенциал возобновляемой энергетики для Южно-Уральской железной дороги. *Энерго- и ресурсосбережение. Энергообеспечение. Нетрадиционные и возобновляемые источники энергии: материалы Международной научно-практической конференции студентов, аспирантов и молодых ученых, посвященной памяти профессора Данилова Н. И. (1945–2015) – Даниловских чтений (Екатеринбург, 11–15 декабря 2017 г.).* Екатеринбург : УрФУ, 2017. С. 804–807.

6. Сущенко К.Б. Оптимізація споживаної електроенергії при застосуванні нетрадиційних джерел живлення. *Електромагнітна сумісність та безпека на залізничному транспорті.* 2017. № 14. С. 80–85. DOI: 10.15802/ecsrt2017/137789.

7. Electricity production in Ukraine. URL : https://kosatka.media/uk/category/elektroenergiya/analytics/proizvodstvo-elektroenergii-v-ukraine-u-vie-znachitelnyy-rirost.].

8. ДСТУ 3466-96 Якість електричної енергії. Терміни та визначення. Київ, 1998. 22 с.

9. Тарифи на електроенергію для домогосподарств України. URL : http://www.nerc.gov.ua/data/filearcli/catalogl/Prezentatsia_optymizatsia_taryfiv_na_electro.pdf.

10. Закон України «Про електроенергетику»: редакція від 01.01.2019. Верховної Ради України. URL : https://zakon.rada.gov.ua.

11. Закон України, щодо встановлення «Зеленого» тарифу. URL : http://zakon4.rada.gov.ua/laws/show/601-17.

12. Національний план дій з відновлюваної енергетики на період до 2020: редакція від 01.10.2014 / Кабінет Міністрів України. URL : https://zakon.rada.gov.ua/laws/show/902-2014-%D1%80.

13. Лежнюк П.Д., Комар В.О., Кравчук С.В., Котилко І.В. Прокопенко І. О. Оцінювання якості електропостачання в локальних електричних системах з різнотипними відновлюваними джерелами енергії. *Вісник Харківського національного технічного університету сільського господарства. Серія «Проблеми енергозабезпечення та енергозбереження в АПК України».* № 195. 2018. С. 23–25.

14. Кудря С.О. Стан та перспективи розвитку відновлюваної енергетики в Україні. *Вісник Національної академії наук України*. 2015. № 12. С. 19–26. URL : http://nbuv.gov.ua/UJRN/vnanu.

15. Каплун В.В. Удосконалення перетворювального агрегату комбінованої системи електроживлення з поновлюваними джерелами енергії. *Електротехнічні та комп'ютерні системи*. 2016. № 22(98). С. 165–169. URL : http://etks.opu.ua/core/getfile.php?id=l 810.

16. Качан Ю.Г., Кузнецов В.В. Щодо практичного застосування відновлюваних джерел енергії в системах живлення нетягових споживачів. *Гірнича електромеханіка та автоматика. Науково-технічний збірник*. № 102. Дніпро, 2019. С. 21–25.

17. Собственные нужды подстанций. Электросети. URL : http://pue8.ru/elektrotekhnik/903-sobstvennye-nuzhdy-podstantsij.html.

18. Прохорский А.А. Тяговые и трансформаторные подстанции. Москва : Транспорт, 1983. С. 436–441.

19. Індустрія вітроенергетики в Україні набирає оберти. URL : https://energytransition.in.ua/industriya-vitroenergetyky-v-ukrayini/.

20. Будько В.І. Розроблення математичної моделі роботи автономної зарядної станції електромобілів від вітроелектричних установок. *Відновлювана енергетика*. 2017. № 3. С. 6–13.

21. John Sun Car Battery Efficiencies. URL : http://large.stanford.edu/courses/2010/ph240/sunl/.

22. URL : http://byd.iproaction.coni/ua/vehicle/e6.htm.

23. Diaf S., Belhamel M, Haddadi M., Louche A., A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy*, Volume 35. Issue 11, pp. 5708–5718, 2007.

24. Кудря СО., Будько В.І. Вступ до спеціальності. Нетрадиційні та відновлювані джерела енергії: Електронний курс лекцій. Київ : Національний технічний університет України («КПІ»). 2013. 360 с.

25. Портал відкритих даних. URL : http://data.gov.ua.

26. Будько В.І. Автономні енерговузли на основі відновлюваних джерел енергії з різними системами акумулювання енергії. *Відновлювана енергетика*. 2015. № 2. С. 21–25.

27. Кудря С.О. Нетрадиційні та відновлювані джерела енергії : підручник. Київ : НТУУ «КПІ», 2012. 492 с.

28. Wasynczuk O. Dynamic behavior of a class of photovoltaic power systems. IEEE Transactions on Power Apparatus and Systems 102 (1983) 3031-3037.

29. Phang J.C.H., Chan D.S.H., Philips J.R. Accurate analytical method for the extraction of solar cell model parameters J.C.H. Phang, D.S.H. Chan, J.R. Philips Electronics Letters 20 (1984) 406-408.

30. Кудря С.О. Підвищення ефективності акумулювання енергії вітру в автономних системах. *Відновлювана енергетика*. 2009. № 2. С. 25–31.

31. Photovoltaic Modules [Електронний ресурс] – Режим доступу : https://www.mitsubishielectricsolar.com/iiTiages/uploadsdocuments/specs/MLU_spec sheet 250W 255W.pdf

32. Лежнюк П.Д., Рубаненко О.Є., Гунько І.О. Вплив інверторів СЕС на показники якості електричної енергії в ЛЕС. *Вісник Хмельницького національного університету*. 2015. № 2(223). С. 134–145.

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