Andrii DEINEKO
Pavlo KRUKOVSKYI
Gennadii FROLOV
Institute of Engineering Thermophisics,
Heat and Mass Transfer Modeling Laboratory,
2a, Marii Kapnist str., Kyiv, 03057, Ukraine
Corresponding author: andriideineko@gmail.com

Doi: 10.53412/jntes-2023-1-2

FEATURES OF THE HEAT AND MASS TRANSFER OF THE UNDERGROUND STRUCTURES OF THE KIEV METRO WITH THE GROUND MASS AND AIR ENVIRONMENT

Abstract: *On the basis of the experimental values of temperature and absolute humidity of the tunnel air and the temperature of the walls of the rim of the deep tunnels of the Kyiv metro, the features and mutual influence of the earthen massif, the supply air environment and the operating modes of the mechanical system of reversible tunnel ventilation during the year are considered. On the basis of the CFD model, which takes into account the above processes of heat and mass transfer, ventilation modes have been determined that have made it possible to reduce the humidity of a group of tunnels of the Kyiv metro as much as possible.*

Keywords: *subway, tunnel, humidity, air, ventilation, modeling*

Introduction

In today's world, the subway is a popular form of underground public transport in any major city with heavy street traffic. In the capital of Ukraine, this function is performed by the Kyiv Metro, in addition, during martial law, the underground part of the metro additionally serves as a shelter for the population. In general, the Kyiv Metro system consists of 46 underground and 6 surface stations on three branches with a total length of 67.6 km. The underground part of subway lines consists of tunnels of shallow (to a depth of 10-12 m), medium (12 to 20-25 m) and deep (more than 25 m) occurrence. There are the following forms of cross-sections of tunnels: rectangular (shallow tunnels), circular (tunnels constructed by mechanized method), vaulted (walkers and ventilation tunnels).

Experience in the operation of subways shows that the well-being of passengers and the performance of maintenance personnel are significantly affected by hygienic conditions, as well as the state of the air and microclimate in tunnels and structures. It has been established that the main harmful components in the subway are heat, moisture and carbon dioxide, released from the transformation of energy spent on the movement of trains and the operation of equipment, from the vital activity of passengers and maintenance personnel, as well as various gases that can enter the tunnel with outside air, from soils, communications crossing tunnels and located next to them. In addition, dust generated in the tunnels and arriving with ventilation air, oil mist and microbiological air pollution are harmful to the subway. As a rule, the outside air supplied to the tunnels is not processed (due to the high costs of this process) [1].

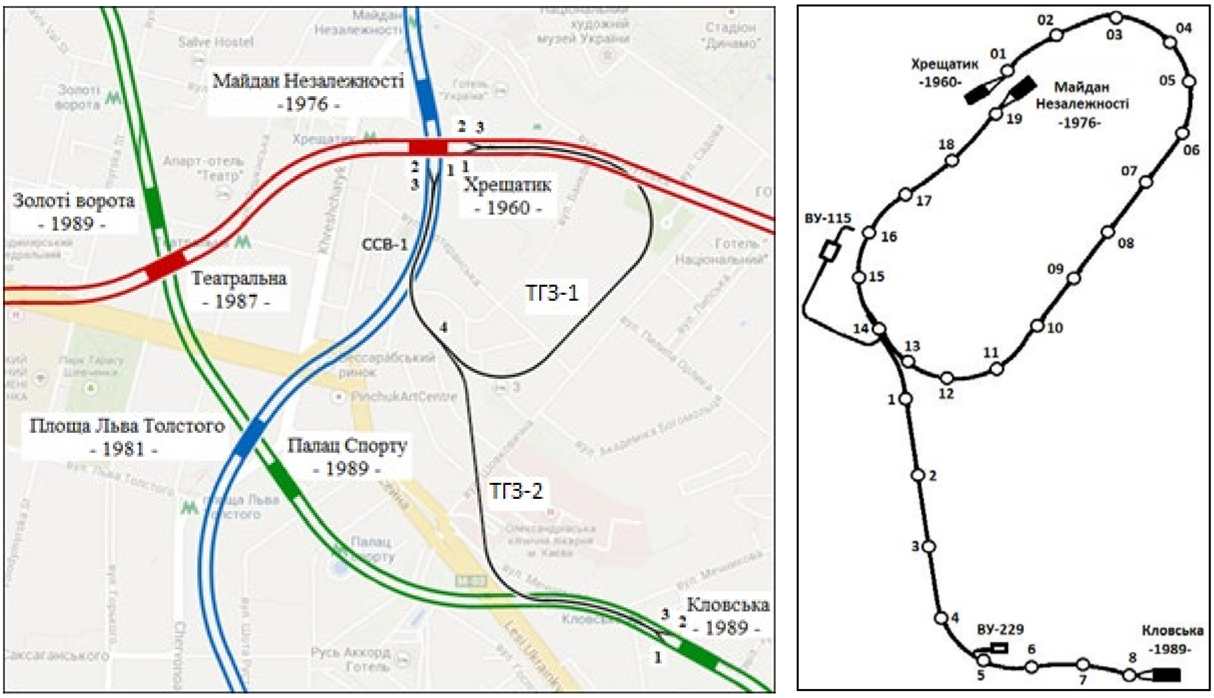
The objective of ventilation in stations and tunnels is not only to maintain specified meteorological conditions (air temperature from +5°C to +28°C, relative humidity less than 75%) and chemical composition of the air, which meet hygienic requirements, but also to create necessary modes of ventilation in case of malfunction of subway devices and smoke formation in places of passengers and staff [1]. Components of the mechanical system of reversible tunnel ventilation of the Kiev subway are ventilation units (VU), located directly near the stations and in separate ventilation shafts (VSh). The operation of the tunnel ventilation system is regulated by a work schedule throughout the year, depending on the temperature and humidity of the environment. The reversibility of the mechanical ventilation system of subways consists in the fact that during the warm period of the year outside air is forced into the tunnel through the station ventilation shafts and/or inclined escalator tunnels and is removed to the surface through the distillation ventilation shafts, and vice versa during the cold season [1].

Defining the goal and objectives of the study. Analysis of peculiarities and regularities of changes in heat and mass transfer characteristics of deep tunnels by the example of the Kiev subway as a result of mutual influence of the earth mass with the air environment depending on the modes of operation of the mechanical system of reversible tunnel ventilation during the year.

The geometric, physical, and mathematical models are described in detail in [1].

Research results

From September 2017 to December 2018, the authors, together with the staff of the electromechanical service of the Kiev subway, conducted experimental studies of the temperature and absolute humidity of tunnel air and the temperature of the walls of the rim of deep tunnels (Figs. 1-4).



a) b)

FIGURE 1. *Scheme of the subway tunnels (ST): a) schematic location of ST between the metro stations (m. sta.): 1-4 – numbers of track switches; Khreshchatyk – 1960 – name of the subway station and year of construction, respectively; b) marking of subway tunnels pickets: 01-19 – numbers of ST-1 pickets; 1-8 – numbers of ST-2 pickets*

Experimental studies were carried out during metro working hours, taking into account the "pumping" effect of train traffic, using the testo 835-T1 pyrometer and testo 435-T1 thermoanemometer in accordance with the recommendations of V.Ya. Tsodikov [2].

During the trial period from September 22, 2017 to August 15, 2018, station ventilation units and VU 229 operated in steady state with a flow rate of 108000 m^3/hour, and VU 115 – 215000 m^3/hour. Injection of air in the tunnel was carried out by VU of stations and VU 229, and removal of tunnel air through VU 115. It should be noted that this mode of operation of VU has remained unchanged over the past 20 years. As a result of a complex and ramified tunnels network, the distribution of air flow in tunnels directions is as follows: from the Khreshchatyk metro station to the junction – 7 m³/sec; from the Klovska metro station to the junction – 29 m³/sec; from the Maidan Nezalezhnosti metro station to the junction – 23 m³/sec.

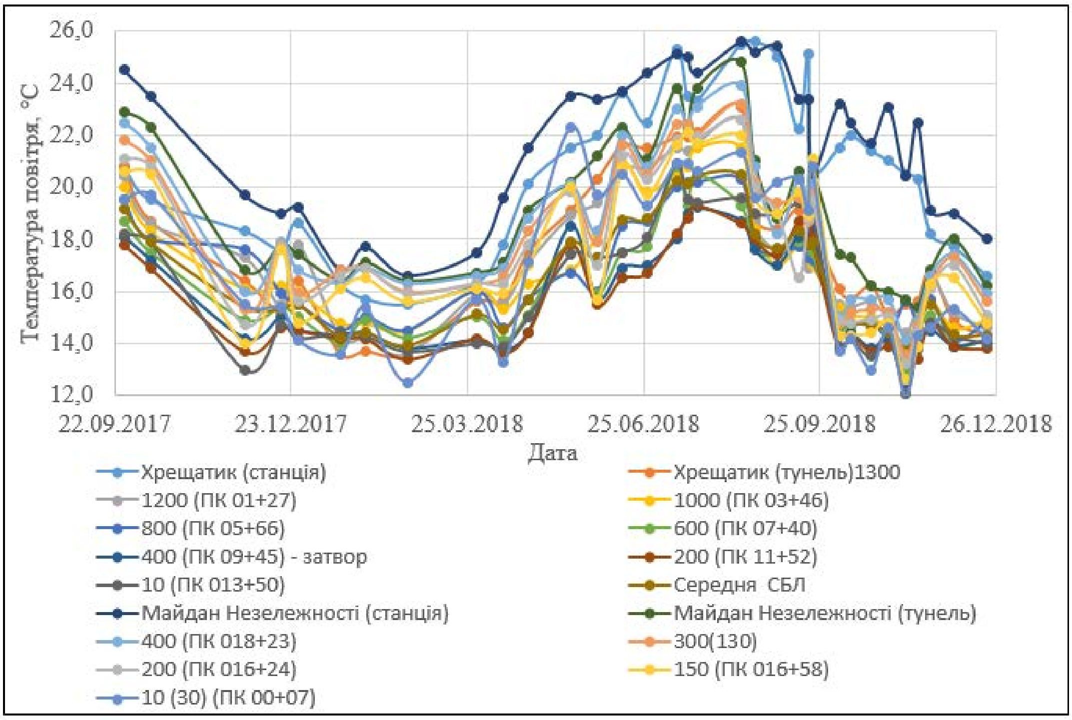


FIGURE 2. *Variation of tunnel air temperature during 2018 for different pickets on the ST-1 section from Khreshchatyk m. sta. to Maidan Nezalezhnosti m. sta.*

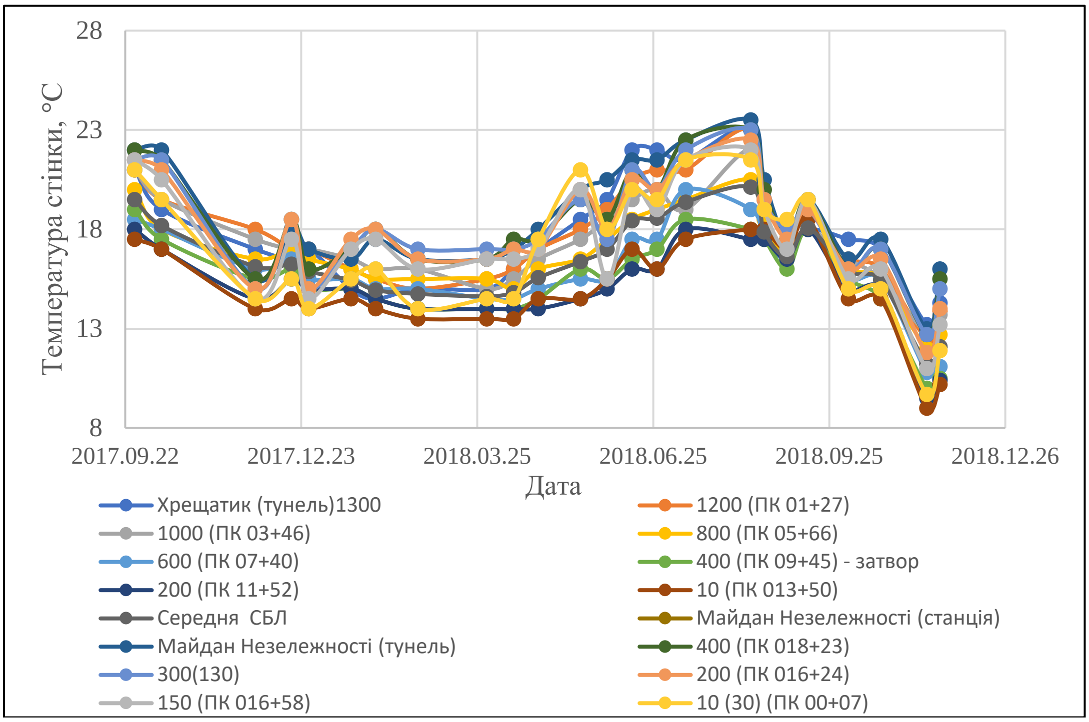


FIGURE 3. *Changes in the temperature wall of the tunnel rim walls during 2018 for different pickets on the ST-1 section from Khreshchatyk m. sta. to Maidan Nezalezhnosti m. sta.*

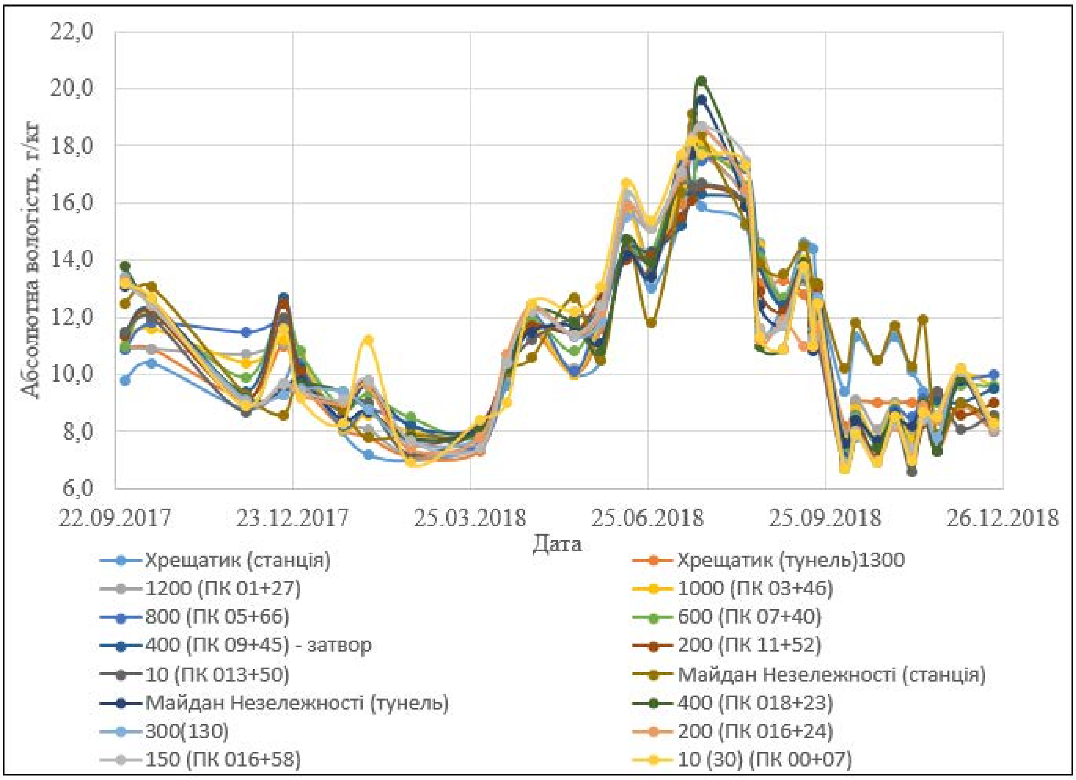


FIGURE 4. *Changes in the absolute humidity of tunnel air during 2018 for different pickets on the ST-1 section from Khreshchatyk m. sta. to Maidan Nezalezhnosti m. sta.*

As can be seen from Figures 2 and 3, the temperatures of tunnel air and tunnel rim wall are characterized by the fact that at stations are always higher than in tunnels, this is due to the heat input from passengers at stations during the winter period and the injection of warm air at stations during the summer period. Also, Figures 2-4 shows that the temperature and absolute humidity of tunnel air and the temperature of the tunnel rim wall change cyclically throughout the year according to the summer and winter modes of operation of the mechanical system of reversible tunnel ventilation: the lowest values are characteristic of the winter mode, and the highest ones of the summer mode, the extreme values are characteristic of the middle of modes. Since the air movement in the ST did not change during the year, so in the summer period the closest sections of the ST to the stations are heated first by convection and begin to accumulate heat by thermal conduction into the soil layer around the tunnels. By the end of the summer period, sections of ST from the stations Khreshchatyk and Maidan Nezalezhnosti in the direction of the junction warm up to 500 m: from PC 19 and from PC 01 to PC 14 and to PC 06, respectively. There is no heat accumulation in the summer period on the section of ST-1 from PK 06 to the junction. During winter mode, these sections of ST-1 from the stations and Khreshchatyk and Maidan Nezalezhnosti begin to cool by convection, resulting in changes in temperature and absolute humidity of tunnel air provides relative humidity close to the normative value of 75%. On the section of ST-1 from PK 06 to the junction the tunnel air is not heated (even at speeds of 0.5 m/s, the maximum value of 4 m/s) and the relative humidity is 95-98%, sometimes in May-July it reaches 100% (the phenomenon of fog). Due to the large mass of building structures of the tunnel mandrel walls and the soil layer around them (large inertness) there is no significant accumulation of heat in summer, so the temperature of the tunnel air and tunnel mandrel walls differ by 1-2°C at most.

For this period by engineering method of Tsodikov [2] accounting for the movement of subway trains and CFD modeling of heat and mass transfer of thermal energy from 10 m layer of soil around the tunnels determined the duration of the summer period of soil heating around the tunnels, which for Kiev is 153 days. The calculated air temperature during the cold period of the year at the stations of the Kiev subway located at a depth of about 60 m, where the amplitude of fluctuations of outside air temperature with natural soil temperature of +10°C does not affect, is +13°C. The calculated duration of heat transfer into the ground for 153 days is 5088 hours. During the summer period, the final air temperature in the tunnel will be close to +23°C, which is confirmed by experimental data for sections of ST-1 up to 500 m long from the stations. The depth of ground warming is 2.8 m. The resulting calculations depend on the intensity of train traffic in the tunnels. Taking into account in the calculations, the correction for the schedule of train traffic, we determine the average annual temperature of the soil around the ST-1 tunnels, equal to +15°C.

Switching the operating modes of the ventilation system is carried out when comparing the ambient temperature and the average temperature of the tunnel air of the ST: switching to the summer mode (forcing VU115 and VU229, removing tunnel air through the VU of stations), when the ambient temperature is equal to or higher than the average temperature of the tunnel air; switching to winter mode (reverse to summer mode) when the ambient temperature is equal to or lower than the tunnel air temperature.

The implementation of the proposed mode of operation of the mechanical reversible tunnel ventilation system in the Kiev subway was carried out from 15.08.2018 to 15.11.2018. From Figures 2-4 we can see that during this period the temperature and absolute humidity of the tunnel air along the length of ST-1 leveled off, which led to a decrease in the relative humidity of the tunnel air to the level of 75%. In addition, according to the experimental values of the temperature of the ST-1 rim wall, the section from the connector to PC 07 started to accumulate heat.

Conclusions

On the basis of analysis of experimental values of temperature and absolute humidity of tunnel air and temperature of the tunnel lining wall of deep-flowing tunnels at steady-state operation mode of tunnel ventilation during a calendar year with injection of air in the tunnel from the stations side it was found that a 700 m long tunnel section (with total length 1400 m) does not accumulate heat from tunnel air in summer and leads to high humidity of 95-98%, sometimes 100%. In order to reduce humidity in deep tunnel sections longer than 500 m, it is necessary to install an additional ventilation shaft with a ventilation system. If the tunnel air temperature does not comply with +15°C, the air should be heated by local electrical installations in order to avoid damage to the equipment.

Thanks to the CFD model for deep tunnels, a reversible tunnel ventilation mode was defined and proposed, the implementation of which led to a decrease in the humidity of tunnel air in the problem area to 75-80%. The peculiarity of tunnel reversible ventilation in summer is the injection of air by the overrun VUs and removal by the station VUs, and vice versa for winter period. This solution is due to the complex geometry of the metro tunnels.

References

[1] Krukovskyi P.G., Deineko A.I., Diadiushko Ye.V., Skliarenko D.I., 2020, *Calculation and Experimental Analysis and Forecasting of Thermogasodynamic and Moisture Conditions of Underground Tunnels*: Monograph; Edited by P.G. Krukovskyi, Deineko A.I., Kyiv, Franco Pack LLC, 141p., ISBN 978-966-97896-8-6.

[2] Tsodikov V.Ya., 1975, *Ventilation and heat supply of subways*. 2nd edition, revised and supplementary. Moskov: Nedra, 560p.

Petro ZINKEVYCH
Serhii BALIUTA
Iuliia KUIEVDA
National University of Food Technologies,
68 Volodymyrska str., 01601 Kyiv, Ukraine
Corresponding author: petrozinkevich@gmail.com

Doi: 10.53412/jntes-2023-1-3

COMPARATIVE COMPUTATIONAL ANALYSIS OF THE SELECTION OF BATTERY ENERGY STORAGE FOR CIVIL OBJECTS AND PARKING WITH PHOTOVOLTAIC PLANTS

Abstract: *One of the disadvantages of solar power plants is that they do not produce electricity at night, so they cannot support the load of consumers. One of the reliable methods of increasing the efficiency of the use of photovoltaic power station (PPS) for consumers is the installation of energy storage. This study aims to investigate the efficiency of using a battery energy storage system (BESS) that is designed to power a civil facility and a parking lot. This study presents a feasibility analysis of BESS using System Advisor Model (SAM) software. The following objects were chosen as objects of research: a cottage; 19-story residential building with built-in non-residential premises (BNP); 9th floor parking lot for 979 cars. These facilities have solar power plants installed on the roof. BESS is planned to be used for power supply of the entire facility and power consumers. For the existing PPS, taking into account the peak load, the selection of the storage energy and modeling of the system operation modes was performed.*
The modes of use of the usage accumulator have been studied. The most effective mode of operation is mode 1, which involves charging the electricity storage during the day, and feeding the load in the evening. It is advisable to use this mode throughout the year. Mode 2 should be used to cover the load only during the spring-winter-autumn period, when the electricity generation from the FES is not sufficient.
The simulation results showed that BESS has the highest economic efficiency for the electricity supply of BZB with a payback period of 10.5 years with a battery utilization efficiency of 96.49%.

Keywords: *PPS; BESS; System Advisor Model; battery energy storage*

Introduction

Energy production from PPS has a number of advantages and disadvantages. One of the disadvantages is that PPS does not produce electricity at night, so they cannot support the load of consumers. To solve the problem of stability of electricity supply at night battery energy storage (BES) are used [1]. BES in combination with a solar power plant is called a battery energy storage system (BESS). This system absorbs and releases energy in different periods. There is no doubt that the additional investment and operating costs of BESS will affect the cost-effectiveness of the PPS. The purpose of this work is to develop the BESS design methodology of civil objects and parking.

Materials and Methods

In this study, the selection of the BES and the simulation of the operation modes of the PPS, which is installed on the roof of civil facilities and a parking lot, are carried out. The system consists of PPS, charge controller, inverter and BES. SAM software was used for research.

The structural diagram of the power supply system with PPS and BES is shown in Figure 1.

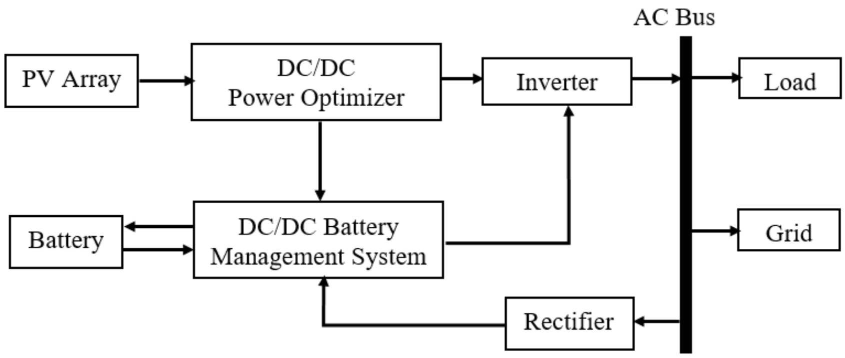


Figure 1. *Model of BESS [2]*

The principle of operation of BESS is that the energy produced in the PPS charges the BES, and then, when there is no solar insolation, the storage is discharged. At the same time, energy can be used to supply electricity to public housing facilities (parking lots) or can be fed into the electrical grid [3].

The selection of an EE storage unit for an existing PPS involves the following stages:

1. Determining the load capacity of public transport facilities (parking lots).
2. Based on the data on the installed capacity of the PPS, the forecast of the annual EE generation.
3. Calculation of the peak annual load in the SAM software.
4. Calculation of the power and capacity of the BES based on the peak annual load.
5. Choice of BES type: lead-acid or lithium-ion.
6. Selection of the mode of use of the BES.
7. Modeling of BESS operating modes in the SAM software to determine the value of the generated energy of the PPS and evaluate the efficiency of using the BES.
8. Economic analysis and evaluation of the economic performance of the hybrid system using the SAM software, taking into account the daily, monthly and annual volumes of electricity generated by the PPS, BES data and electricity consumed by the facility.

Results and Discussions

In this work, calculation studies of efficiency using BES for power supply of objects using PPS were carried out. The research objects are located in the city of Kyiv (latitude: 50.4; longitude: 30.45). Weather data was selected for 2021 from (https://energyplus.net/weather).

Table 1. *Deviation of air temperature in the room from the average. Design loads and parameters of PPS with peak load (option 1)*

Type of house	Nominal power of the existing PPS, kW	Estimated power of consumers (AC), kW	Estimated power of power consumers (AC), kW	Peak annual power of consumers (AC), kW	Peak annual power of power consumers of BZHB (AC), kW
K	60	25	–	40	–
B	124.95	–	16.32	–	26
A	676.2	398	–	151.49	–

For comparison, a BES for half the peak load was selected.

TABLE 2. Design loads and parameters of the PPS with half the peak load (option 2)

Type of house	Nominal power of the existing PPS, kW	Estimated power of consumers (AC), kW	Estimated power of power consumers (AC), kW	Half of the peak annual power of consumers (AC), kW	Half peak annual power of power consumers (AC), kW
K	60	25	–	20	–
B	124.95	–	16.32	–	13
A	676.2	398	–	75.75	–

K – cottage; B – 19-story residential building with built-in non-residential premises (BNP); A – 9th floor parking lot for 979 cars. The cottage is powered only by PPS. The PPS of a residential building is used to supply energy consumers. The parking lot is powered only by the PPS.

Using the calculated parameters of the peak load, the capacity of the BES is determined. The storage was selected taking into account the condition that the peak load should be less than the nominal power of the PPS. A Vipow lithium-ion (lithium-iron-phosphate) battery with a capacity of 50Ah and a voltage of 3.2 V was selected for the designed PPS. For each object of research using the SAM software, the selection of the choice of BES, the time of operation at maximum power and the capacity BES. The results of the calculations are presented in Tables 3 and 4.

TABLE 3. Selection of BES and capacity (option 1)

Variant number	The power of the BES consumers (DC), P1	Time of operation at maximum power, t1	Capacity of the BES of consumers (DC), Q1 = P1 · t1
K	32	2	64
B1	21	4	128
B2	21	8	258
B3	21	12	384
A1	152	4	608
A2	152	8	1216
A3	152	12	1824

TABLE 4. Selection of BES and capacity (option 2)

Variant number	The power of the BES of consumers (DC), P2	Time of operation at maximum power, t2	Capacity of the BES of consumers (DC), Q2 = P2 · t2
K1	20	2	40
B4	13	4	52
A4	76	4	304

With the use of SAM software, the following modes of operation of the BES were simulated by programming the drive dispatch controller:

1. Mode 1: BES charge during the day, feeds the load in the evening.
2. Mode 2: At night (11:00 p.m. – 7:00 a.m.) it does BES fully charge from the power grid (low electricity tariff), in the morning (7:00 a.m. – 8:00 a.m.) it gives electricity to the electric grid, and then charges from the PPS.

Such working periods are BES defined:

Period 1. All energy from the PPS is directed to battery charging.

Period 2. Discharge of BES and power supply of consumers.

Period 3. Charging of the battery from the electrical grid and subsequent return of energy from the BES to the electrical grid.

The BES discharge is carried out gradually: the BES will be discharged every hour by 20% of the total 80% depth of discharge. This will allow for an even discharge of the battery system during each hour of peak time. The minimum state of charge is 20% and the maximum state of charge is 100%, giving a depth of discharge (DOD) of 80%. This ensures the highest battery life.

The results of BESS modeling for various research objects are presented in Figures 2-10.

1. Cottage. Similar graphs are obtained for other variants of the cottage study.

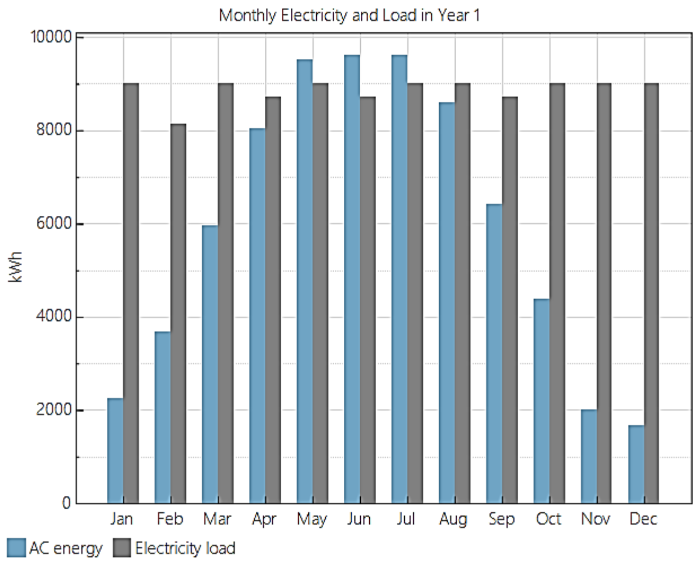


FIGURE 2. *Schedule of average monthly electricity production of the PPS and consumption of the facility K*

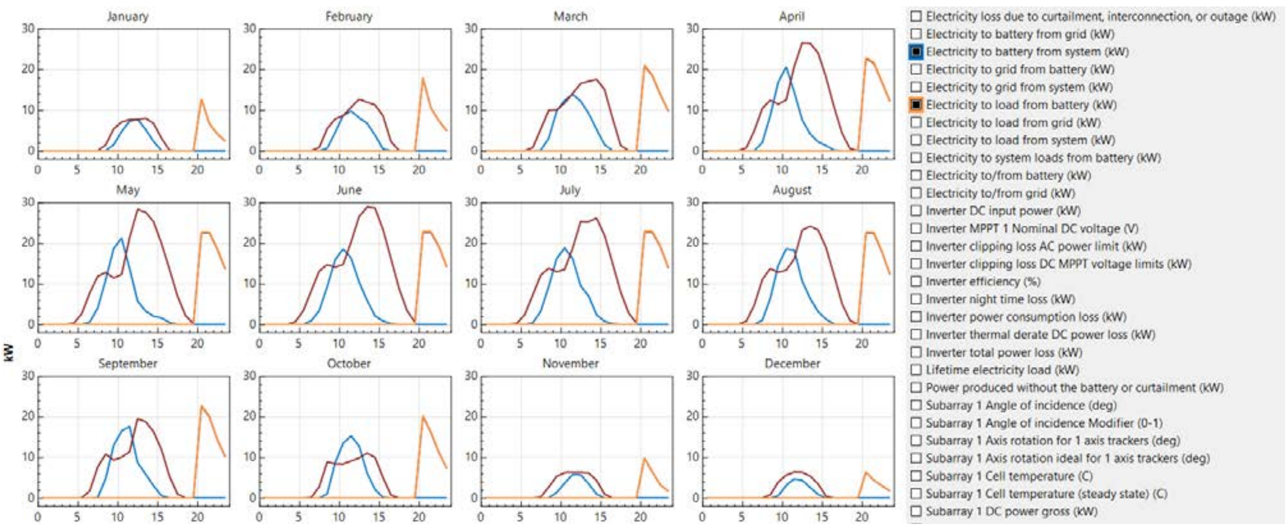


FIGURE 3. *Graphs of the average monthly electricity generation of the PPS, the electricity that is stored and the electricity that is delivered to the consumer according to mode 1*

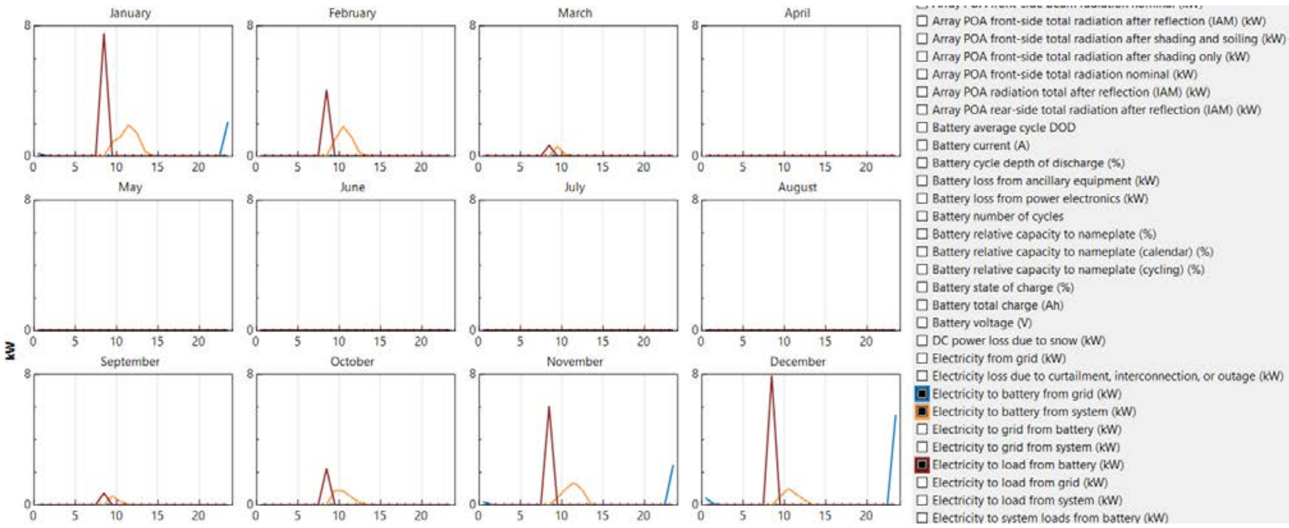


FIGURE 4. *Graphs of electricity accumulated from the PPS and the electrical grid and electricity delivered to the consumer in mode 2*

2. 19-story residential building with built-in non-residential premises (BNP). Similar graphs were obtained for other variants of the BZH study.

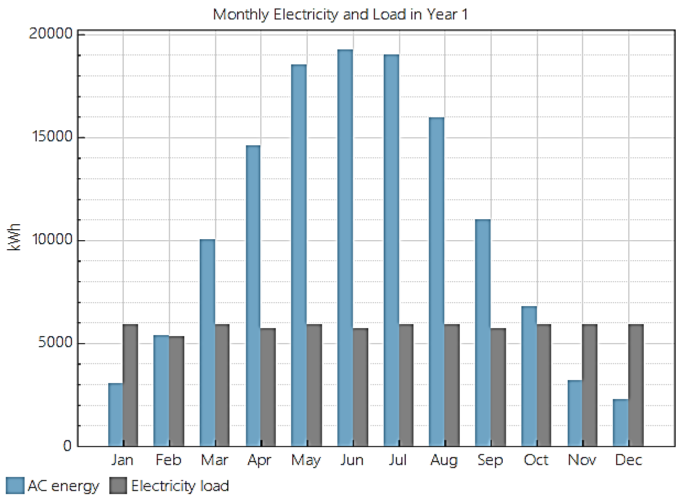


FIGURE 5. *Schedule of average monthly electricity production of the PPS and consumption of facility B*

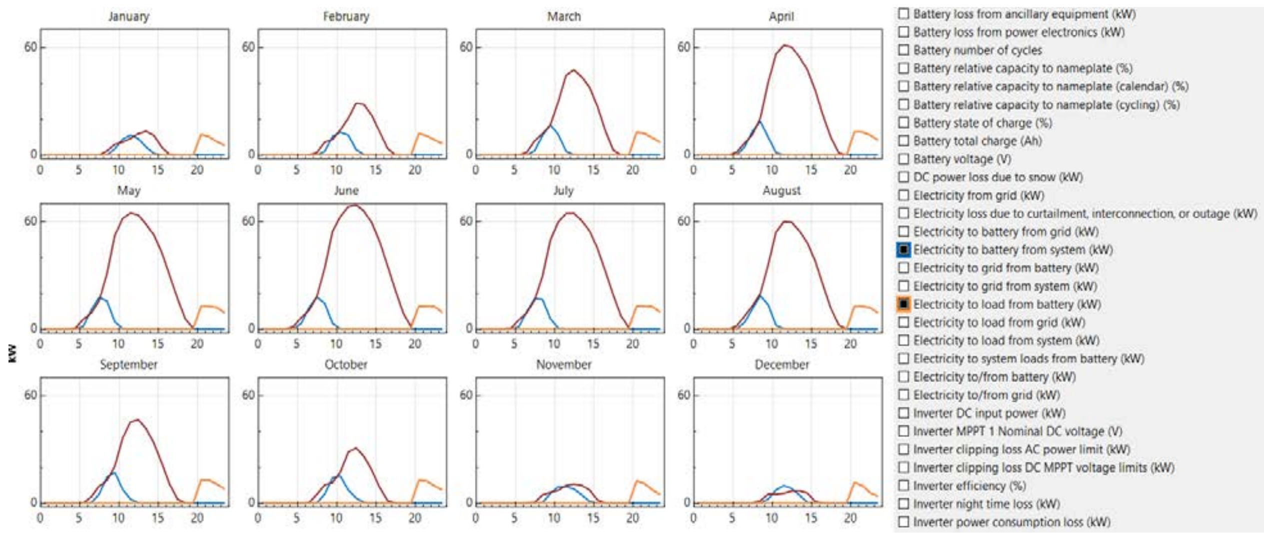


FIGURE 6. *Graphs of the average monthly electricity generation of the PPS, the electricity that is stored and the electricity that is delivered to the consumer according to mode 1*

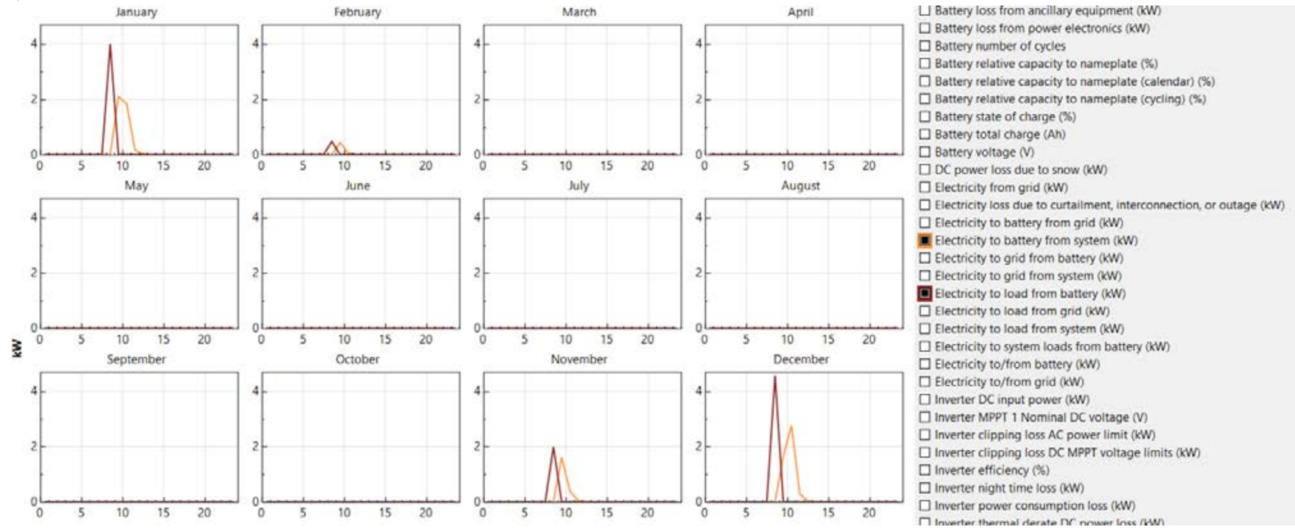


FIGURE 7. *Graphs of electricity accumulated from the PPS and the electrical grid and electricity delivered to the consumer in mode 2*

3. 9th floor parking lot for 979 cars. Similar graphs are obtained for other variants of the parking lot study.

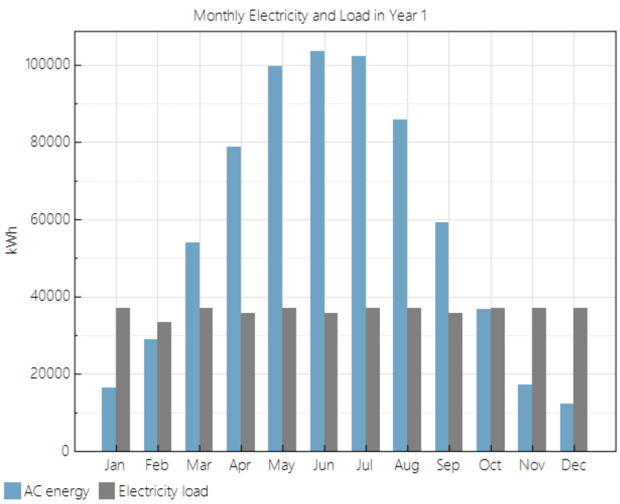


FIGURE 8. *Schedule of average monthly electricity production of the PPS and consumption of object A*

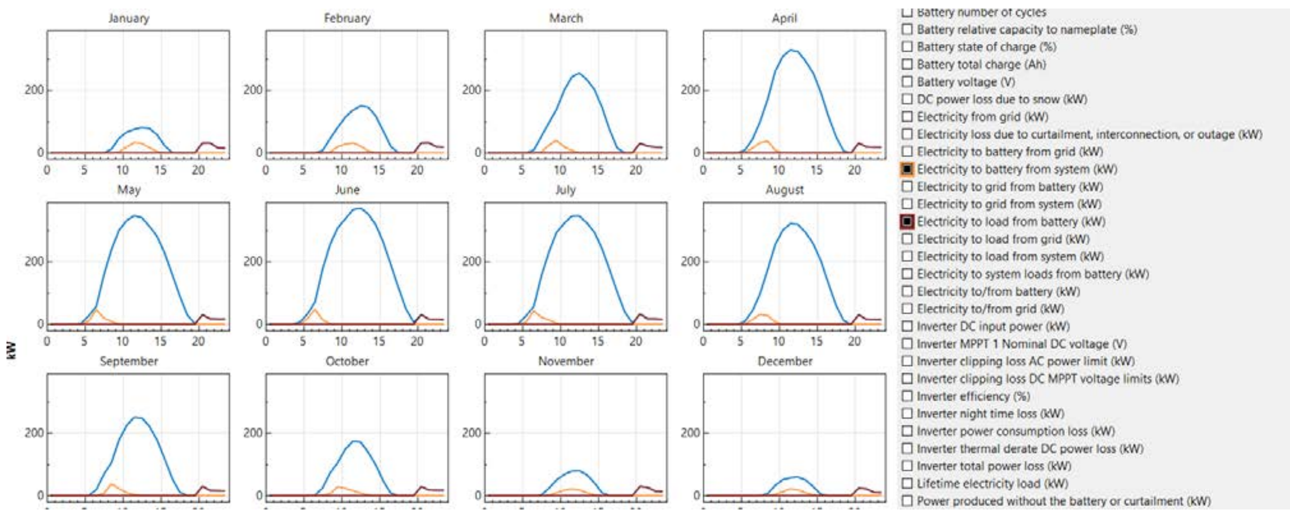


FIGURE 9. *Graphs of the average monthly electricity generation of the PPS, the electricity that is stored and the electricity that is delivered to the consumer by mode 1*

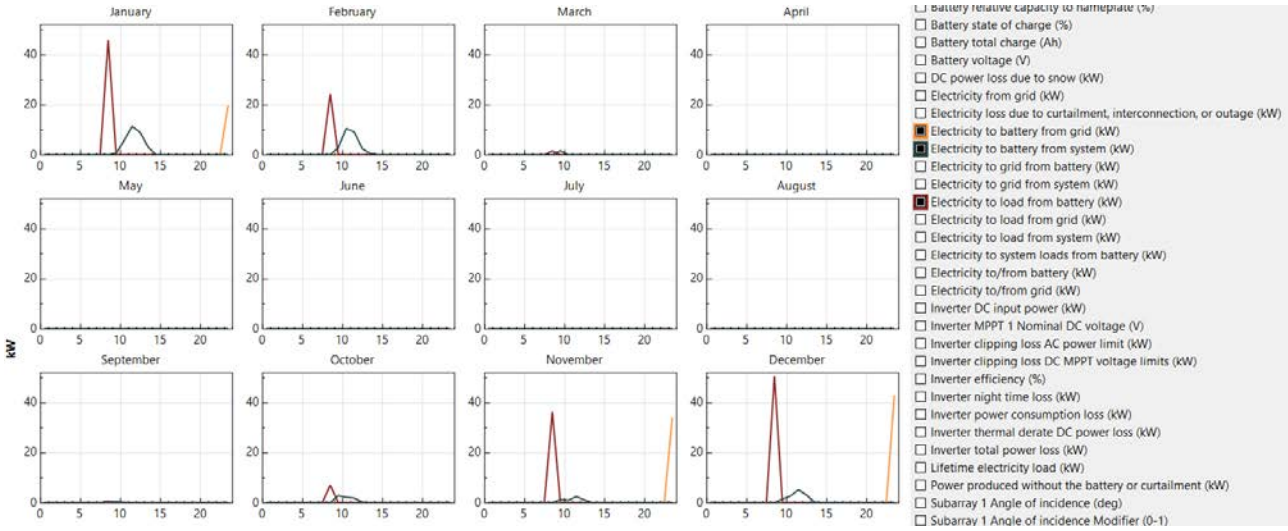


Figure 10. *Graphs of electricity accumulated from the PPS and the electrical grid and electricity delivered to the consumer in mode 2*

Comparing Figures 2, 5 and 8, it can be concluded that the energy of the PPS is not enough to cover the load during the spring-winter-autumn period. Using mode 1 shown in Figures 3, 5 and 8 BES is charged during the day, in the evening it supplies the load for a year. Mode 2, shown in Figures 4, 7 and 10, the BES, is used only to cover the load during the spring-winter-autumn period, when there is not enough electricity.

Using the calculated parameters of BESS, an economic assessment of projects of electricity supply of research objects with the use of PPS was performed.

The results of the economic assessment of BESS design for various research objects are presented in Table 5.

Table 5. *Results of the economic evaluation of the BESS project*

Mode of use of the electricity storage	Total cost of BESS construction	Battery efficiency	Battery charge energy from PPS	Payback period
Mode 1 for K	$133763	94.60%	100.0%	13.2
Mode 2 for K	$133763	95,48%	71.9%	13.1
Mode 1 for B1	$230152	94.98%	100.0%	12.5
Mode 1 for B2	$254415	96.01%	100.0%	14.6
Mode 1 for B3	$278238	96.28%	100.0%	17
Mode 2 for B1	$230152	96.44%	100.0%	12.5
Mode 2 for B2	$254415	96.61%	100.0%	14.6
Mode 2 for B3	$278238	96.67%	100.0%	16.9
Mode 1 for A1	$1359378	94.44%	100.0%	11.6
Mode 1 for A2	$1488894	95.58%	100.0%	13.7
Mode 1 for A3	$1618411	95.8%	100.0%	16.1
Mode 2 for A1	$1359378	92.12%	45.4%	13.2
Mode 2 for A2	$1488894	94.12%	45.8%	15.9
Mode 2 for A3	$1618411	94.88%	45.9%	19
Mode 1 for K1	$127464	94.2%	100.0%	12.7
Mode 2 for K1	$127464	94.98%	100.0%	12.5
Mode 1 for B4	$219431	94.5%	100.0%	11.7
Mode 2 for B4	$219431	95.85%	99.7%	11.7
Mode 1 for A4	$1264194	92.62%	100.0%	10.5
Mode 2 for A4	$1264194	96.28%	52.0%	11.3

Analysis of the data given in the Table 5 showed that the project with the use of PPS for powering the parking lot in mode 1 for A4 with a payback period of 10.5 years has the highest economic efficiency. For civilian objects, the most effective project is a B4-19-story residential building with a payback period of 11.3 years and a cost of $219,431.

Conclusions

1. For the most efficient use of the power supply system with PPS and storage throughout the year, it is advisable to use mode 1, which involves charging the BES during the day, and feeding the load in the evening.
2. Mode 2 should be used to cover the load only during the spring-winter-autumn period, when the generation electricity from the FES is not sufficient.

References

[1] Salkuti S.R., 2018, *Comparative analysis of storage techniques for a grid with renewable energy sources*. Salkuti S.R., Chan M.J., International Journal of Engineering and Technology, Vol. 7, Iss. 3, pp. 970-976.

[2] Pirthi T., 2020, *Performance analysis of pv and bess based hybrid system for residential load volume*. Pirthi T., Tanu P., International Journal of Current Engineering And Scientific Research, Vol. 7, Iss. 3, pp. 18-22.

[3] Feisal A., 2020, *Application of behind the meter battery storage system integrated with net metering in Indonesia*. Feisal A., Sudiarto B., Setiabudy R., IOP Conference Series: Earth and Environmental Science, pp. 1-6.