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Optimization of power dispatching schedule of a charging station based on a micro grid with a photovoltaic module

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ABSTRACT

The world is on a course toward total electrification of vehicles. In the near future, most vehicles will run on electric power. One of the main reasons for users' dissatisfaction with electric vehicles is the lack of public direct current charging stations. Since electric vehicles charging can cause an additional increase in peak load on the grid, the optimal solution is direct current charging stations with photovoltaic generation with a micro grid architecture. If the charging station has a connection to the public grid, then, provided that the solar energy and storage system are optimally utilized, the station aggregator's profit can be increased by selling excess energy to the grid. This paper analyzes the charging habits of customers at direct current charging stations. It was found that the peak demand for charging is observed around 9:00 and 14:00-17:00, the same time as the general peak load on the grid. Thus, the peak charging demand coincides with the peak grid load and increases the net peak of the system. However, this excess demand on the system in the form of charging load can be met by the installed solar photovoltaic system, as the output power of the photovoltaic system is sufficient to meet the charging demand during the peak hours of solar radiation. Thus, for the considered direct current charging station, the optimization problem of dynamic economic dispatch was formulated, since the generation and load schedules change over time. The goal of optimization is to minimize the cost of primary energy. This problem, formalized as a mixed integer linear programming problem, was solved using the interior-point solver of the GEKKO library in Python. Four scenarios for the operation of the station were worked out, in summer and winter, with a fixed and dynamic electricity tariff. According to the results of the study, it was found that in the conditions of a fixed tariff in the summer, the cost of primary energy can be reduced 2.5 times, in fact, increase profits, thanks to the sale of electricity to the public grid. In winter, the use of the optimization algorithm of the station will provide an insignificant cost savings due to low photovoltaic generation. Under the conditions of a dynamic tariff that corresponds to the prices on the day-ahead market, using the optimization algorithm, it was found that for this experimental variant of the station's operation, the maximum profit in summer will be 207.60 UAH, while in winter the cost of primary energy will be 177.47 UAH. The results obtained indicate that the operation of a charging station under dynamic tariffs in the day-ahead market in Ukraine is a promising direction for the development of charging infrastructure in the country and proves the possibility of efficient use of renewable energy sources. Thus, this paper analyzes the global experience of developing charging stations based on micro grids, the integration of renewable energy sources into them, and approaches to building electricity dispatch schedules. The financial feasibility of the station's operation in the context of the electricity market in Ukraine was also investigated.

Keywords: Electric vehicles; direct current charging station; photovoltaic generation; micro grid; power dispatching schedule; mixed integer linear programming optimization

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INTRODUCTION

The widespread adoption of electric vehicles (EV) is a major development trend in the automotive industry worldwide. With zero emissions and low noise levels, EVs are an ideal solution to environmental problems and the shortage of fossil fuels. The main obstacles to the spread of EVs are the lack of charging infrastructure [1], charging time, and limited range [2, 3].

Charging EVs can become a serious problem and increase the load on the national grid, as charging electric vehicles throughout the day will increase the peak load. This can be prevented by developing charging stations based on micro grids with renewable energy sources. Photovoltaic systems can be installed on carports or on the rooftops of buildings and connected to a charging station, which in turn can operate in island mode or in grid-connected mode. Since the nature of solar radiation is intermittent and highly dependent on the season and time of day, which can cause both excess and shortage of solar generation, it is important that charging stations are equipped with an energy storage system. This will allow storing excess energy and using the accumulated energy when generation is low. Due to the volatility of renewable energy sources (RES), the stable operation of the charging station is ensured by the micro grid architecture with a connection to the public grid. If EVs are charged with green energy, the market for EVs will be encouraged, as EVs will help minimize the environmental footprint of transportation.

A random or uncoordinated approach to EV charging has a negative impact on the distribution network, including increased real power losses, sharp voltage fluctuations, network overload, the need to increase grid capacity, and expensive charging. Coordinated charging can improve the operational performance of a power company by intelligently managing the charging load of EVs and minimize the cost of charging by adopting a dynamic price policy [4]. Charging is managed by an agent called an aggregator [5].

The charging station aggregator can also benefit by participating in the energy market and selling extra energy back to the grid through the photovoltaic to grid (PV2G) concept. Using the available data on load demand, photovoltaic power, and storage capacity available at the charging station, the optimal charging algorithm can be calculated to maximize profits.

ANALYSIS OF LITERARY DATA

Approaches to solving the problem of minimizing the cost of primary energy for a charging station are very well covered in the literature. The paper [6] found that the use of batteries and renewable energy sources at fast charging stations can reduce the operating costs of the charging station, and also has a positive impact on the power system. In order to determine the optimum power of the generating unit and the type of battery, taking into account the number of charge cycles, the discharge depth and the battery life, the problem was formulated in terms of mixed-integer linear programming (MILP). The optimal solution shows that the energy storage system (ESS) and renewable energy sources can reduce costs by 35%, and the peak load can be reduced by almost 8%. In the paper [7] profit maximization in an electricity market with dynamic prices where the charging station is directly connected to the grid is considered. In [8] an algorithm for reducing operating costs taking into account customer satisfaction is proposed. Customers are to respond to changing electricity prices, decide whether they prefer to charge or discharge, and actively regulate charging rates and times [9]. So the authors proposed an intelligent method of controlling charging loads of electric vehicles in response to the price of time of use (TOU) in the regulated market. The goal is to minimize charging costs and maximize discharge profits. To minimize the cost of charging, taking into account the ratio between the acceptable charging capacity of the electric vehicle battery and the state of charge (SOC), a heuristic method is implemented. Also [10] presents an EV charging model based on real-time price information, considering the preferences of individual vehicles as well. If we take into account the computational time of large optimization problems, heuristic algorithms are superior to direct optimization. The solution found by heuristic algorithms may not be the best, but should not deviate significantly from the solution obtained by direct optimization. In the work [11] the forecast of solar photovoltaic energy and the probability of the appearance of electric vehicles is considered to optimize the operation of an autonomous commercial charging station based on a solar photovoltaic system with a battery energy storage system (BESS) for maximum profit. The method of MILP is used to determine the optimal solution. The authors of [12] investigate the problem of optimizing energy costs taking into account the periodic arrival and departure of electric vehicles. MILP is formulated as a real-time optimization problem to minimize the total energy cost while taking into account the physical constraints of the system.

THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this work is to develop a power dispatching schedule of a charging station based on a micro grid with a photovoltaic module in such a way as to minimize the cost of primary energy for the charging station.

The research tasks are to analyze the charging habits of EV owners and schedule day-ahead power dispatch according to PV-generation forecast.

DIRECT CURRENT MICROGRID ARCHITECTURE

The electric vehicle charging station is based on direct current (DC) micro grid and under limited power conditions, it consists of photovoltaic (PV) module, public grid, electrochemical storage system (ESS) and electric vehicles. DC micro grid sources are connected to a common DC bus. Fig. 1 shows the DC micro grid architecture of the charging station. When the EV arrives, the driver selects the charging mode. Electricity produced by photovoltaic sources is mainly intended for charging EVs. The storage system is an additional source of energy for charging electric vehicles or for absorbing excess energy produced by photovoltaic sources. The public grid is used as a back-up source, allowing PV to sell excess energy, or buy in shortages. If the PV power is lower than the power required by the EVs, the additional power needed to charge the EVs is provided first by the storage and then by the public grid. On the contrary, excess energy is primarily fed to the storage device, and then fed into the public grid. Vehicles are the only load.

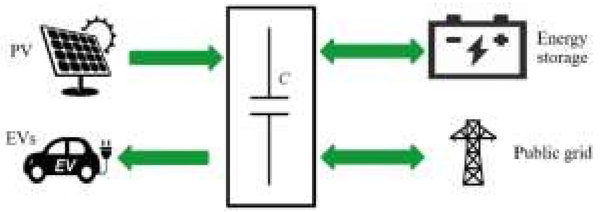

Fig. 1. **Direct current micro grid for electric vehicle charging station**

Source: **compiled by the authors**

Photoelectric module. The proposed charging station for electric vehicles is based on 86 photovoltaic panels (Risen RSM110-8-550M Mono PERC Half-Cell), the power of one module is 550W under standard conditions of solar radiation of 1000 W/m2 and ambient temperature of 25°C. PV power is calculated in the MPPT mode as given by (1) and (2):

$$P_{PV\ MPPT}(t_i) = P_{PV\ STC} * \frac{g(t_i)}{1000} * [1 + \gamma(T_{PV}(t_i) - 25)] * N_{PV}; \quad (1)$$

$$T_{PV}(t_i) = T_{amb}(t_i) + g(t_i) * \frac{NOCT - T_{air\_test}}{G_{test}}, \quad (2)$$

where $P_{PV\ STC}$ is PV power under standard test conditions (STC); g is insolation level; $\gamma = -0{,}29\%/°C$ is temperature coefficient of power; T_{PV} is temperature of the photovoltaic cell; N_{PV} isnumber of photovoltaic panels; T_{amb} is ambient temperature; $NOCT = 41{,}5°C$ is the nominal operating temperature of the cell; $T_{air\_test} = 20°C$ is fixed air temperature; $G_{test} = 800$ Вт/м^2 is fixed solar radiation for testing.

The energy storage system is a battery. Due to its high energy density, high discharge capacity, long life cycle, fast charge/discharge, Li-ion battery dominates the portable electronic sector and has become the best choice in the automotive sector. In addition, in micro grid they are used as ESS, which plays an important role in the integration of renewable energy sources. In addition, acting as a buffer system to mitigate grid congestion, the efficiency of the power system is improved [13]. The lithium-ion battery model is based on the Tremblay battery model [14].

Lithium-ion batteries (in the storage system and electric vehicles) are charged according to the constant current / constant voltage (CC/CV) rule with three charging modes (Fig. 2).

In CC mode, the charging current remains constant until the voltage rises to the cut-off voltage. When the battery starts charging, the voltage is relatively low. If the charging current is not constant, the life cycle of the battery and the charger will be shortened. When the battery is almost fully charged, the process enters the constant voltage (CV) phase, which aims to prevent the battery from overcharging. In CV mode, the voltage remains constant and the current drops. This CC/CV procedure is assumed to be controlled by a battery management system already integrated into the PEV battery system [16, 17]. Although usually electrical circuit models for individual cells are studied, in this survey battery packs consisting of multiple cells connected in series are considered based on the Nissan Leaf's battery pack [18, 19].

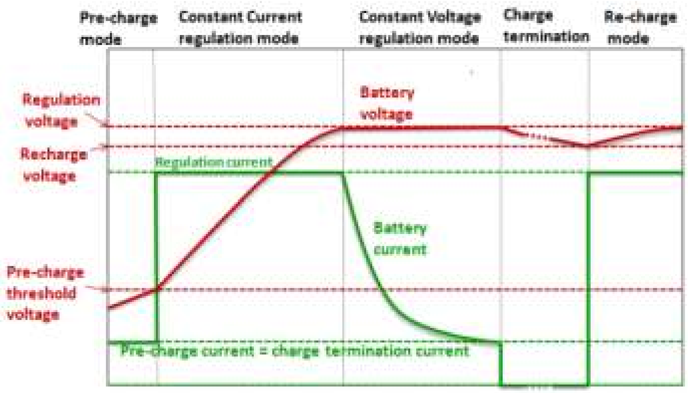

Fig. 2. **Change in current and voltage when charging a lithium-ion battery according to the constant current / constant voltage rule**

Source: **compiled by the [15]**

The voltage v_{charge} and current i_{charge} during the CC phase is calculated according to formulas (3)-(4)

$$v_{charge}(t) = V_{OC}(SoC(t)) - Ri_{CC}; \quad (3)$$

$$i_{charge}(t) = i_{CC} \quad t < t_s, \quad (4)$$

where R is resistance of the battery (assumed to be constant); t_s – denotes the moment when the terminal voltage is equal to the predetermined maximum voltage V_{CV}.

Open-circuit voltage and current during the CC stage, V_{OC} and i_{CC} respectively, are expressed in equations (5) and (6):

$$V_{OC}(SoC(t)) = E_0 - \frac{K}{SoC(t)} + +Ae^{(-BQ(1-SoC(t)))}; \quad (5)$$

$$i_{CC} = \frac{V_0 - \sqrt{V_0^2 - 4P_B(0)R}}{2R}, \quad (6)$$

where E_0 is constant voltage of the battery, K – polarization constant; Q is nominal capacity of the battery.

The parameters A and B represent the amplitude and the time constant, which are inverse in the exponential zone of the curve $V_{charge} = \mathrm{f}(SoC)$.

Finally, $V_0 = V_{OC}(SoC(0))$ and $P_B(0)$ is the battery power profile. When the voltage reaches the predetermined maximum voltage level V_{CV}, equation (7), the charging phase switches from CC to CV.

$$V_{CV} = V_{OC}(SoC(t)) - R \cdot 3600 \cdot Q \cdot SoC(t). \quad (7)$$

The voltage v_{charge} and current i_{charge} during the CV phase is calculated according to equations (8)-(9)

$$v_{charge}(t) = V_{CV}; \quad (8)$$

$$i_{charge}(t) = 3600 \cdot Q \cdot SoC(t) \quad t \geq t_s. \quad (9)$$

Battery charging and discharging must be monitored to ensure proper operation, avoiding overcharging or deep discharging. To do this, a battery management system is used to regulate the SOC, which is between 20 % and 80 %, as shown in (10):

$$SoC(\%) = SoC_0(\%) - 100 \cdot \frac{\int idt}{Q}. \quad (10)$$

Public grid. The considered public grid is a low-voltage network characterized by an phase-to-phase voltage of 400 V and a frequency of 50 Hz. The modeling of the connection to the public grid is based on the inverter model.

The micro grid energy management system monitors and controls the operation of each DC micro grid module. Based on the monitoring data, the energy management system controls the charging power of the electric vehicle and the power supplied by the photovoltaic system, the energy storage system or the distribution network. The micro grid energy management system helps to achieve distributed photovoltaic energy, EV charging optimization and micro grid balance.

To plan the load dispatching schedule of the charging station, it is necessary to have a forecast for the day in advance regarding the generation of electricity by photovoltaic modules. It is assumed that there are day-ahead forecasts for PV generation.

A typical charging demand profile for a fast charging station for one day was studied in [20] and is shown in Fig. 3. As can be seen from the charging demand curve, the peak charging demand is observed at the same time when the peak load on the grid occurs. In this way, the peak charging demand coincides with the peak load of the grid and increases the net peak of the system. This excess demand in the system in the form of a charging load can be met by an installed solar PV system, as the output power of the solar PV is sufficient to meet the charging needs during peak hours of solar radiation. This will eliminate the conversion losses that occur when EVs are charged from the grid. If the charging demand is not too high, the energy available from the solar PV system can be fed into the grid.

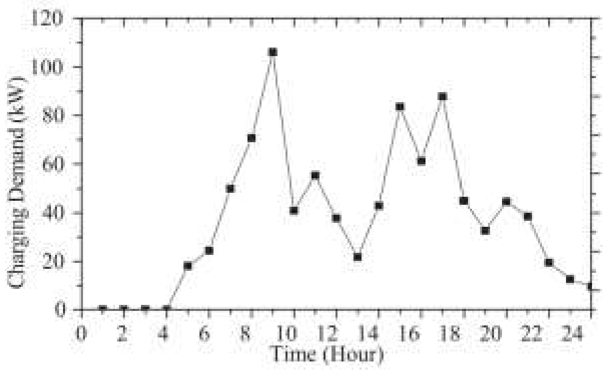

Fig. 3. **Expected charging demand of a fast charging station on a weekday**
Source: **compiled by the [20]**

OPTIMIZATION PROBLEM

The total cost of energy takes into account the cost of electricity supplied from the grid, the profit from electricity injected into the grid, the cost of wear of the electrochemical storage battery during operation. Thus, the objective function is to minimize, given by equation (11):

$$\min \rightarrow C_{total} = C_G + C_S;$$
$$C_G = \sum_{t_i=t_0}^{t_F} \left[c_G(t_i) \cdot \Delta t \cdot (p_{G\_S}(t_i) - p_{G\_I}(t_i)) \right]; \quad (11)$$
$$C_S = \sum_{t_i=t_0}^{t_F} \left[c_S(t_i) \cdot \Delta t \cdot (p_{S\_C}(t_i) + p_{S\_D}(t_i)) \right],$$

where C_G, C_S is the cost of energy from the grid and the cost of wear and tear of stationary storage; c_G, c_S are the corresponding tariffs.

The cost minimization problem is subject to the following restrictions:

The physical law of power balancing, equation (12):

$$P_{PV}(t_i) = P_S(t_i) + P_G(t_i) + P_{EV}(t_i).\ t_i = \{t_0, t_0 + \Delta t, t_0 + +2\Delta t, \ldots, t_F\}. \quad (12)$$

Equation (13) indicates that the output power of the photovoltaic module is calculated according to equation (1).

$$p_{PV}(t) = p_{PV\_MPPT}(t). \quad (13)$$

Stationary storage, represented by lithium-ion batteries, must be protected from overcharging and overdischarging; thus, the maximum capacity of the storage device, eq. (14), and the maximum and minimum charge levels (state-of-charge, SOC) of the storage device, eq. (15), must be observed to extend the storage life.

$$-P_{S\_max} \le p_S(t) \le P_{S\_max}; \quad (14)$$

$$SOC_{S\_min} \le soc_S(t) \le SOC_{S\_max}. \quad (15)$$

The power sold and purchased from the public grid must be within the established limits, eq. (16):

$$-P_{G\_max} \le p_G(t) \le P_{G\_max}. \quad (16)$$

Electric vehicle charging mode, expressed by equation (17), should be observed as well:

$$0 \le p_{EV}(t) \le P_{EV\_Mode\_max}\ \forall t \in [t_{arr}, t_{dep}], \quad (17)$$

where $Mode$ is the selected charging mode: slow, medium, fast.

The charging level of the electric vehicle when sent must be no more than the one chosen by the client and no more than the maximum permissible, which is expressed by the equation (18),

$$SOC_{EV\_min} \le SOC_{EV\_arr} \le SOC_{EV\_dep} \le \le SOC_{EV\_des} \le SOC_{EV\_max};$$
$$SOC_{EV}(t+1) = SOC_{EV}(t) + + \frac{p_{EV}(t)\Delta t}{E}\ \forall t \in [t_{arr}, t_{dep}]. \quad (18)$$

The formulated optimization problem is called dynamic economic dispatch, since the generation and load schedules change over time. Considering the formulation from the equations with given constraints/limits, it can be seen that the problem has the form of MILP. The goal is to minimize the plant operation cost (primary energy cost) given in equation (11), subject to given constraints.

As a software tool for optimization, GEKKO was chosen – an object-oriented Python library that offers model building, analysis tools and visualization of simulation and optimization. GEKKO specializes in dynamic optimization problems for mixed-integer, nonlinear, and differential algebraic equation (DAE) problems. By combining the approaches of typical algebraic modeling languages (AML) and optimal control packages, GEKKO greatly facilitates the development and application of tools such as nonlinear model predicative control (NMPC), real-time optimization (RTO), moving horizon estimation (MHE), and dynamic simulation. The interior-point solver (IPOPT), which is very often used in similar problems, was chosen as the solver [21].

EXPERIMENT AND RESULTS

Current case study was conducted as a theoretical possibility of developing a fast electric vehicle charging station for the city of Odessa. The meteorological data on solar insolation were taken considering the region.

The Fig. 4 shows the randomly generated options: five electric cars arrive for charging. Peak hours are conventionally accepted as 12:00-13:00 and 15:00-16:00. Energy tariffs are chosen arbitrarily to prioritize the sources used to charge electric vehicles. The cost of operating ESS is 1 UAH/kWh, which is lower than the tariff for electricity from the grid, 6 UAH/kWh, therefore ESS is prioritized over GRID, input data is given in Table 1. For models with TOU, the tariff is shown in Fig. 11, energy tariffs only consider operation and do not take maintenance or levelized cost of energy into account, as the life cycle of the sources is not taken into account. Once the aggregator doesn`t satisfy client`s demand penalty is paid, which is 50 UAH/kWh for an unsupplied energy.

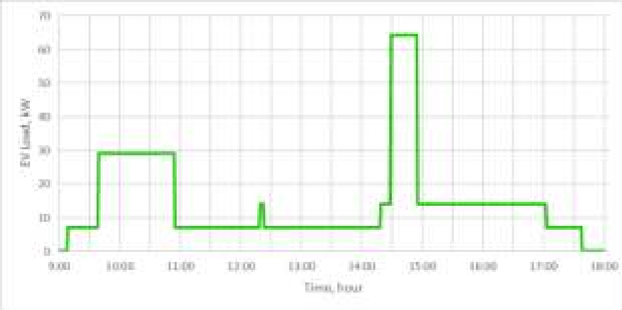

Fig. 4. **Estimated car load schedule**
Source: **compiled by the authors**

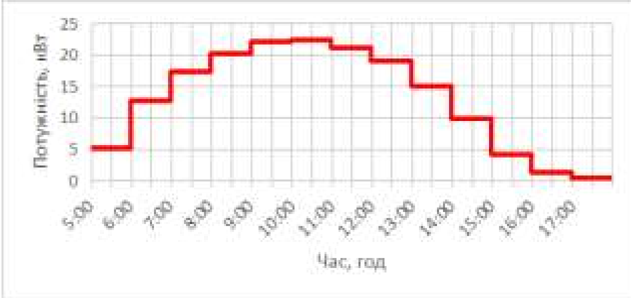

Fig. 5. **Graph of electricity generation by photovoltaic module in summer**
Source: **compiled by the authors**

A total of 4 models were tested: with high and low generation (summer/winter) and under static and dynamic electricity tariff conditions.

Charging station operation in the non-optimized mode means that the grid is used only when the PV and ESS capabilities are exhausted.

Table 1. **Input data**

SOC_{S_min}	20 %	P_{G_max}	50 kW
SOC_{S_max}	80 %	P_{S_max}	34.5 kW
SOC_{S0}	50 %	P_{PV_MPPT}	30 kW
$P_{EV\_fast\_max}$	50 kW	c_G	6 UAH/kWh
$P_{EV\_aver\_max}$	22 kW	c_{EV_p}	50 UAH/kWh
$P_{EV\_slow\_max}$	7 kW	c_S	1 UAH/kWh

Source: **compiled by the authors**

Photovoltaic generation data from [22] for July 10, 2020 (Fig. 5) were taken to simulate the scenario of operation of the charging station in the summer.

In the mode of operation without optimization, power dispatch is shown in Fig. 6, the excess energy generated in the morning hours charges the stationary storage until the maximum SOC level is reached. After that, at approximately 8:29, the excess energy is sold to the grid. The first car is charged entirely from PV. Shortage of PV power is observed when EV1 and EV2 are on the charger at the same time, so the deficit power is supplied from the storage. At 10:56, when EV2 leaves the station, EV1's needs are again met entirely from PV, the excess charging the ESS. Significant power deficit is observed at 14:30 when charging in fast mode becomes EV5. At this time, the predominant power is supplied from the electrochemical storage device, within the maximum permissible power of 34.5 kW. The rest is supplied by the grid and PV, EV3 and EV4 are charged mainly from ESS.

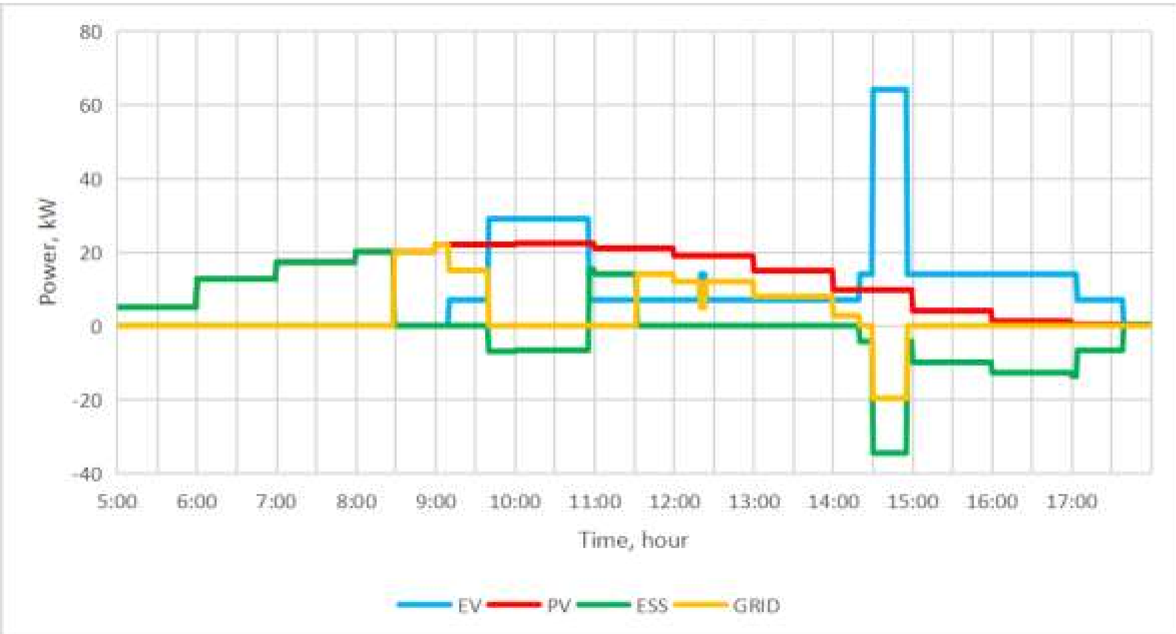

Fig. 6. **Power dispatch in operating mode without optimization (summer)**
Source: **compiled by the authors**

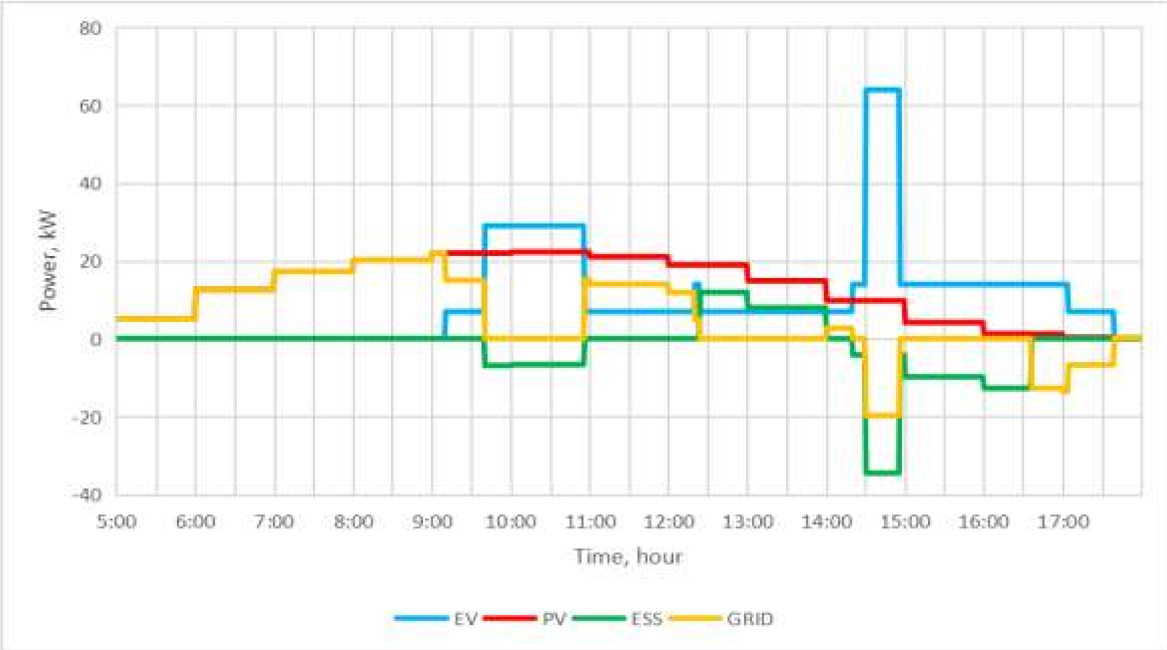

Fig. 7. **Power dispatch in operating mode with optimization (summer)**
Source: **compiled by the authors**

In the operating mode with optimization, power dispatch is shown in Fig. 7, excess energy from PV, which is generated in the morning hours, is sold to the grid. ESS is used to charge EV1 and EV2. From 10:56 AM to 12:23 PM., the excess energy from the PV is sold back to the grid. At the end of the day, the state-of-charge ESS is not enough to charge the EV4, so it is charged by the public grid.

Fig. 8 shows the evolution of state-of-charge ESS for models without and with optimization in summer.

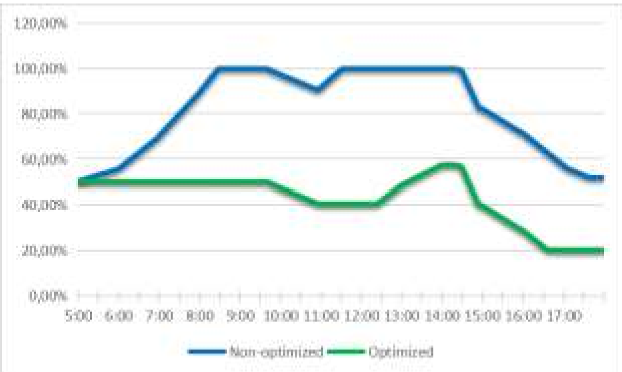

Fig. 8. **Comparison of state-of-charge for modes with and without optimization in summer**
Source: **compiled by the authors**

In the case of operation of the charging station in non-optimization mode, when the goal is to maximize autonomy – using the grid only in case of exhaustion of PV and ESS capabilities, the charging station will sell 48.63 kWh to the grid and purchase 8.55 kWh. 53.46 kWh will be loaded into the battery, 51.87 kWh will be taken from the battery. Taking into account the tariff for operating the storage device, a total of UAH 105.34 will be spent on working with the battery. As a result, the net cost of primary energy for the charging station will be -135.15 UAH. That is, thanks to the sale of electricity to the public grid, the station will earn UAH 135.15.

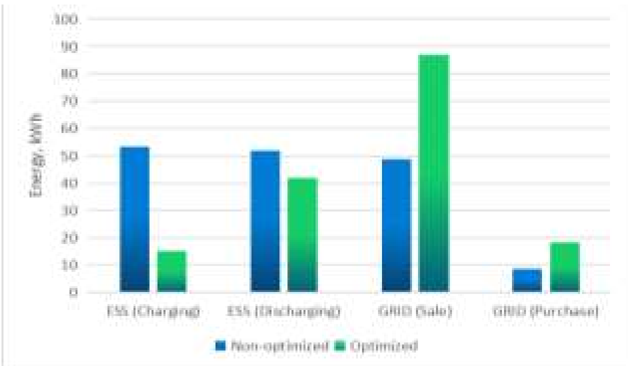

Fig. 9. **Comparison of energy dispatch for modes with and without optimization in summer**
Source: **compiled by the authors**

In the operating mode of the charging station with optimization, optimal values of the variables of the optimization problem are given in Table 2 and the energy dispatch is in Fig. 9, the purpose of which is to minimize the cost of primary energy, 86.95 kWh will be sold to the public grid, and 18.46 kWh will be purchased. Taken from ESS – 41.96 kWh, loaded 15.14 kWh. Taking into account the tariffs, the cost of primary energy for the charging station will be equal to UAH 353.87. The profit of the station compared to the mode of operation without optimization will increase by 2.62 times.

Table 2. **Optimal values of the variables of the optimization problem in summer**

Variable	Without optimization	Optimized
ESS (Charging), kWh	53.47	15.14
ESS (Discharging), kWh	51.87	41.96
GRID (Sell), kWh	48.63	86.95
GRID (Purchase), kWh	8.55	18.46
Cost, UAH	-135.15	-353.87

Source: **compiled by the authors**

To simulate PV generation in winter, data was taken from [22] for December 26, 2020, Fig. 10.

Since solar generation in winter is not enough to charge electric cars, the station will mainly use energy bought from the public grid. In the mode of operation without optimization, the amount of energy sold to the grid is 0, while with optimization, 4.71 kWh can be sold to the public grid.

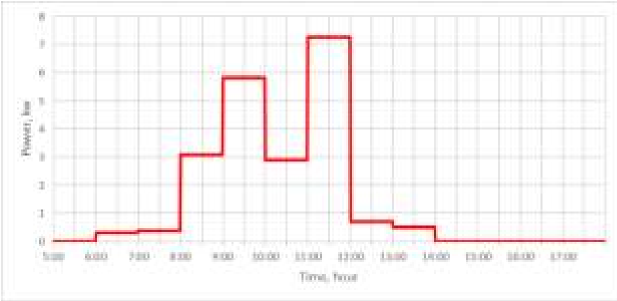

Fig. 10. **Graph of electricity generation by photovoltaic module in winter**
Source: **compiled by the authors**

In the mode of operation without optimization, power dispatch is shown in Fig. 11, the excess energy generated in the morning charges the stationary storage device. There is not enough PV power to charge EV1 and EV2, so the deficit power is supplied from the battery. At 10:53 SOC ESS reaches its minimum, after which the deficit capacity is purchased from the grid. At 11:00, PV generation increases and the excess charges the ESS. After 14:00, PV generation stops and the remaining EVs are fully charged by the public grid.

In the mode of operation with optimization, power dispatch is shown in Fig. 12 excess energy in the morning hours is sold to the grid. EV1 and EV2 due to PV generation deficit are mainly charged from the ESS until it reaches minimum SOC. After that, GRID is used. Excess energy is stored in the ESS between 11 and 12 AM.

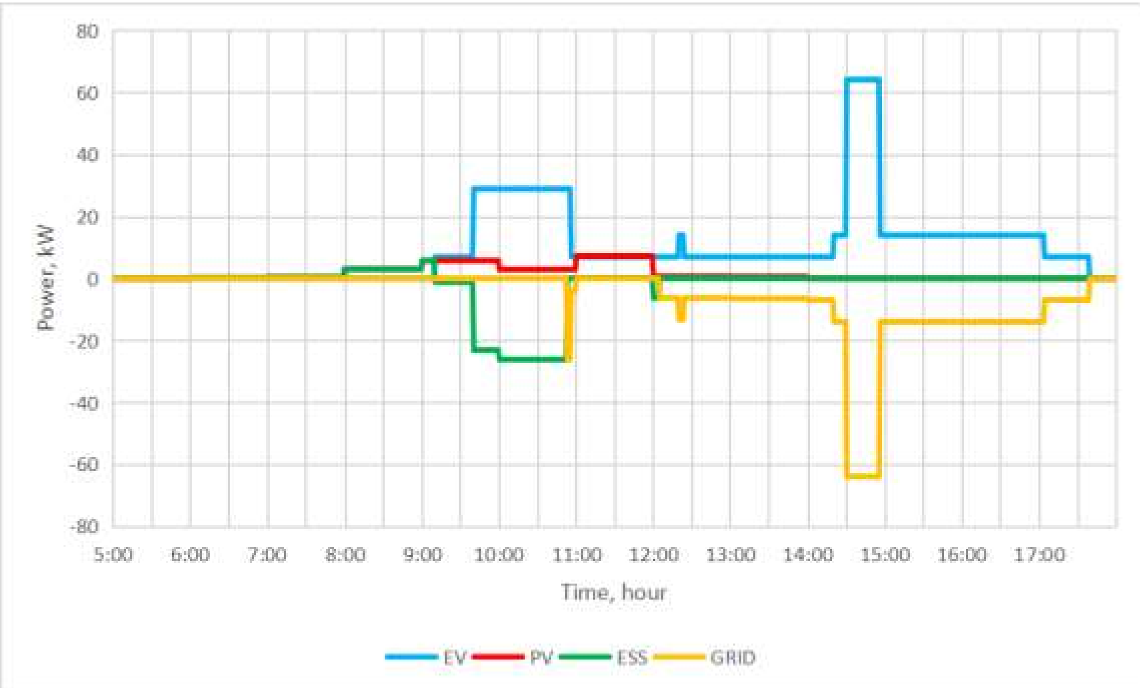

Fig. 11. **Power dispatch in operating mode without optimization (winter)**
Source: **compiled by the authors**

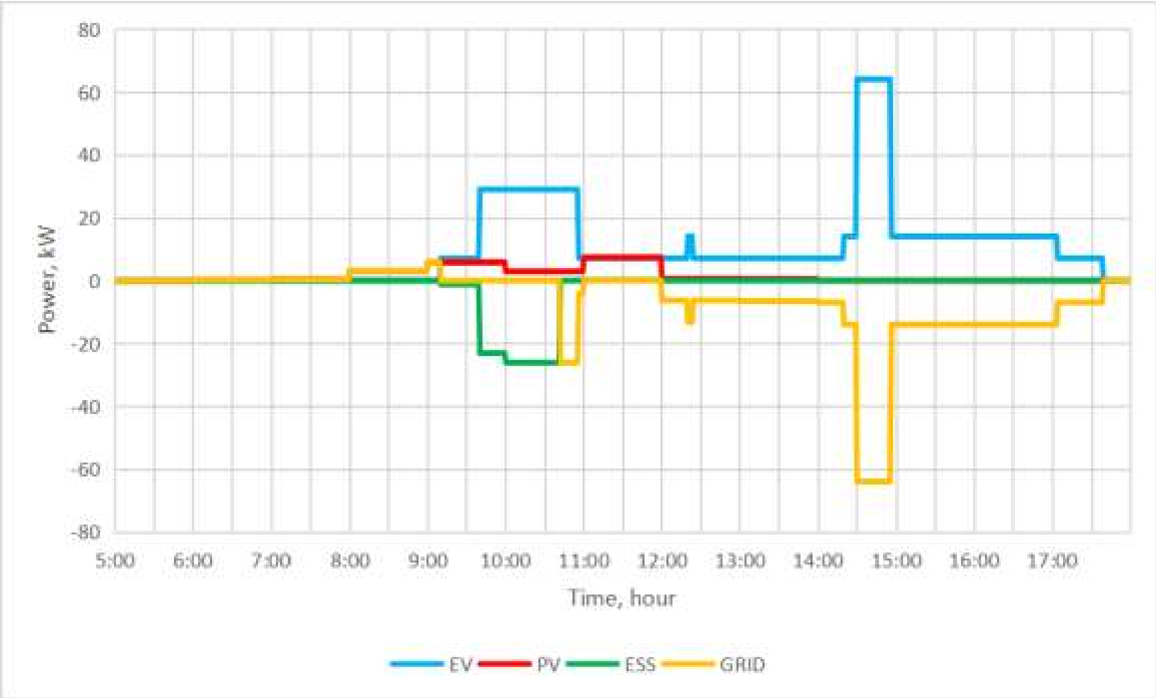

Fig. 12. **Power dispatch in operating mode with optimization (winter)**
Source: **compiled by the authors**

Fig. 13 shows the evolution of SOC ESS for models without and with optimization in winter.

Fig. 13. **Comparison of state-of-charge for modes with and without optimization in winter**
Source: **compiled by the authors**

In the operation mode of the charging station without optimization, 0 kWh will be sold to the public grid and 80.7 kWh will be bought. Taken from ESS – 31.93 kWh loaded 4.95 kWh. Taking into account the tariffs, the cost of primary energy for the charging station will be equal to UAH 521.03. In the operating mode of the charging station with optimization, the purpose of which is to minimize the cost of primary energy, 4.71 kWh will be sold to the public grid, and 86 kWh will be purchased. Taken from ESS – 26.61 kWh loaded 0.24 kWh. Taking into account the tariffs, the cost of primary energy for the charging station will be equal to UAH 514.62. The costs of the station will decrease by UAH 6.41 compared to the mode of operation without optimization.

Optimal values of the variables of the optimization problem in winter is given in Table 3 and energy dispatch in Fig. 14.

Table 3. **Optimal values of the variables of the optimization problem in winter**

Variable	Without optimization	Optimized
ESS (Charging), kWh	4.95	0.24
ESS (Discharging), kWh	31.93	26.61
GRID (Sell), kWh	0	4.71
GRID (Purchase), kWh	80.69	86
Cost, UAH	521.03	514.62

Source: **compiled by the authors**

In 2019, Ukraine introduced a liberalized model of the electricity market. This model allows charging station aggregators to participate in auctions and sell green energy at market prices. Therefore, a dispatch schedule was generated under TOU conditions. The model of the station operating under conditions of dynamic changes in the tariff on the day-ahead market is built using data on the cost of electricity at the day-ahead market in Ukraine [23] for 10.07.2023, Fig 15.

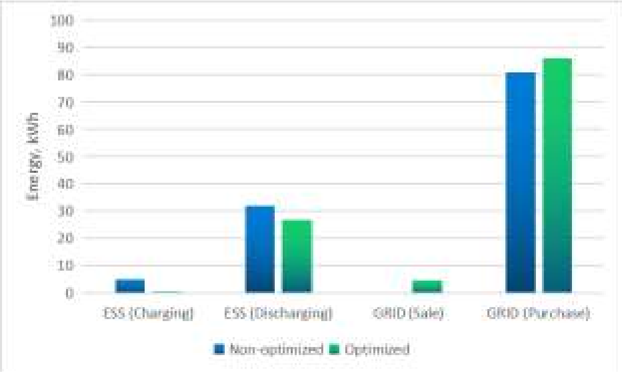

Fig. 14. **Comparison of energy dispatch for modes with and without optimization in winter**
Source: **compiled by the authors**

In the operating mode of the charging station with optimization in the summer, 81.70 kWh will be sold to the grid, 13.85 kWh will be purchased. 20.39 kWh will be accumulated to ESS, 47.39 kWh will be taken from ESS. In winter, under the conditions of the same TOU, 4.71 kWh will be sold to the grid, 80.60 kWh will be purchased, 0.24 kWh will be accumulated to the ESS, 27 kWh will be taken from the ESS. Considering TOU, operation of the station in summer will bring a profit of UAH 207.60, in winter the cost of primary energy will be UAH 177.47.

4. CONCLUSIONS

The operation of a DC charging station in summer and winter was simulated. The load schedule (parking) of electric vehicles was chosen randomly, taking into account possible peak hours. In the TOU model, the electricity tariff was taken from the historical data of day-ahead market auctions. Having formulated the problem of minimizing the cost of primary energy for a charging station in the form of a MILP problem, it was solved using the IPOPT algorithm using the GEKKO, Python library.

The optimization results showed that using this objective function in the summer, the cost of primary energy can be reduced by 2.5 times, actually increasing the profit, thanks to the sale of electricity to the public grid. In winter, the use of the optimization algorithm of the station's operation will provide an insignificant cost savings due to low photovoltaic generation. Under the conditions of a dynamic tariff that corresponds to the prices on the day-ahead market, using the optimization algorithm, it was found that for this experimental variant of the station's operation, the maximum profit in summer will be 207.60 UAH, while in winter the cost of primary energy will be 177.47 UAH

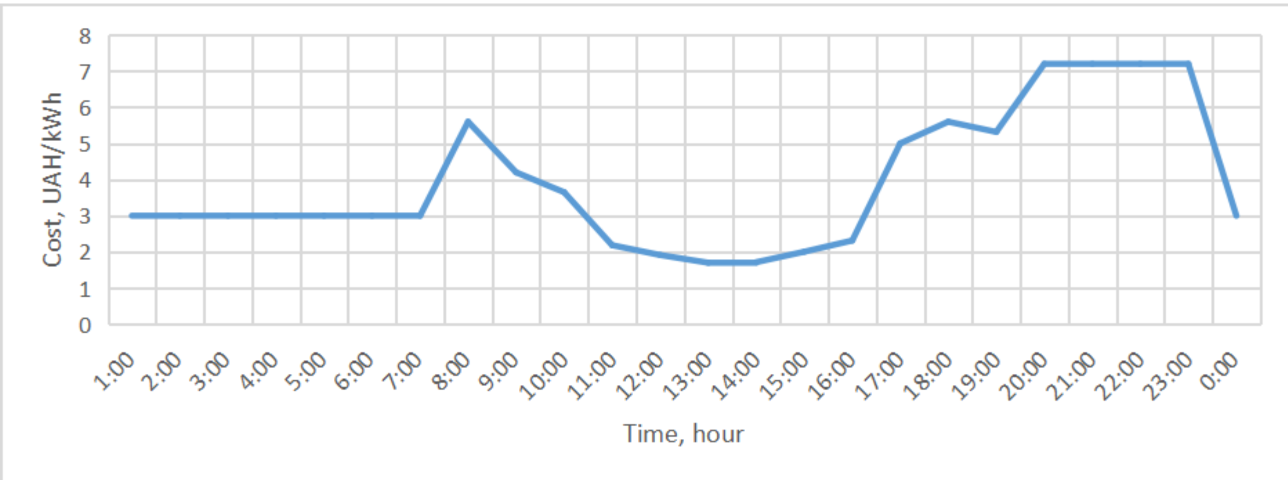

Fig. 15. **Electricity tariffs at the day-ahead market in Ukraine on 10.07.2023**
Source: **compiled by the authors**

REFERENCES

1. Azarova V., Cohen J. J. , Kollmann A. & Reichl J., "The potential for community financed electric vehicle charging infrastructure". *Transportation Research Part D: Transport and Environment*. 2020; 88 (2020): 102541, https://www.scopus.com/authid/detail.uri?authorId=57201123518.
DOI: https://doi.org/10.1016/j.trd.2020.102541.

2. Wassiliadis, N., Schneider, J., Frank, A., Wildfeuer, L., Lin, X., Jossen, A. & Lienkamp, M. "Review of fast charging strategies for lithium-ion battery systems and their applicability for battery electric vehicles". *Journal of Energy Storage* 2021; 44: 103306, https://www.scopus.com/authid/detail.uri?authorId=57194639271. DOI: https://doi.org/10.1016/j.est.2021.103306.

3. Miri, I., Fotouhi, A. & Ewin, N. "Electric vehicle energy consumption modeling and estimation-a case study". *Int. J. Energy Res*. 2021; 45: 501–520, https://www.scopus.com/authid/detail.uri?authorId=43061057600. DOI: https://doi.org/10.1002/er.5700.

4. Amin, A., Tareen, W. U. K., Usman, M., Ali, H., Bari, I., Horan, B., Mekhilef, S., Asif, M., Ahmed, S. & Mahmood, A. "A Review of optimal charging strategy for electric vehicles under dynamic pricing schemes in the distribution charging network". *Sustainability*. 2020; 12: 10160, https://www.scopus.com/authid/detail.uri?authorId=7202593806. DOI: https://doi.org/10.3390/su122310160.

5. Mukherjee, J. C. & Gupta, A. "Distributed charge scheduling of plug-in electric vehicles using inter-aggregator collaboration". *IEEE Trans. Smart Grid*. 2017; 8: 331–341, https://www.scopus.com/authid/detail.uri?authorId=8709864100.
DOI: https://doi.org/10.1109/TSG.2016.2515849.

6. Moradzadeh, M. & Abdelaziz, M. M. A. "A new MILP formulation for renewables and energy storage integration in fast charging stations". *IEEE Transactions on Transportation Electrification*. 2020; 6 (1): 181–198, https://www.scopus.com/authid/detail.uri?authorId=56177898200.
DOI: https://doi.org/10.1109/TTE.2020.2974179.

7. Alghamdi, T. G., Said, D.& Mouftah, H. T. "Profit maximization for EVSEs-based solar energy in smart cities". In *Proceedings of the 2021 International Wireless Communications and Mobile Computing (IWCMC)*. Harbin: China. 2021. p. 1575–1580, https://www.scopus.com/authid/detail.uri?authorId=57225741695. DOI: https://doi.org/10.1109/IWCMC51323.2021.9498933.

8. Yan, Q., Zhang, B. & Kezunovic, M. "Optimized operational cost reduction for an EV charging station integrated with battery energy storage and PV generation". *IEEE Transactions on Smart Grid*. 2019; 10 (2): 2096–2106, https://www.scopus.com/authid/detail.uri?authorId=55510773900.
DOI: https://doi.org/10.1109/TSG.2017.2788440.

9. Li, Y., Han, M., Yang, Z. & Li G., "Coordinating flexible demand response and renewable uncertainties for scheduling of community integrated energy systems with an electric vehicle charging station: A Bi-Level approach". *IEEE Transactions on Sustainable Energy*. 2021; 12 (4): 2321-2331, https://www.scopus.com/authid/detail.uri?authorId=57202365586.
DOI: https://doi.org/10.1109/TSTE.2021.3090463.

10. Selim, A., Abdel-Akher, M., Kamel, S., Jurado, F. & Almohaimeed, S.A. "Electric Vehicles Charging Management for Real-Time Pricing Considering the Preferences of Individual Vehicles". *Appl. Sci.* 2021; 11: 6632, https://www.scopus.com/authid/detail.uri?authorId=56992701400.
DOI: https://doi.org/10.3390/app11146632.

11. Dukpa, A. & Butrylo, B. "MILP-Based Profit Maximization of Electric Vehicle Charging Station Based on Solar and EV Arrival Forecasts". *Energies*. 2022; 15: 5760, https://www.scopus.com/authid/detail.uri?authorId=24483239800. DOI: https://doi.org/10.3390/en15155760.

12. Cheikh-Mohamad, S., Sechilariu, M. & Locment, F. "Real-time power management including an optimization problem for PV-powered electric vehicle charging stations". *Appl. Sci*. 2022; 12: 4323, https://www.scopus.com/authid/detail.uri?authorId=57222118393.
DOI: https://doi.org/10.3390/app12094323.

13. Kouka, K., Masmoudi, A., Abdelkafi, A. et al. "Dynamic energy management of an electric vehicle charging station using photovoltaic power". *Sustainable Energy, Grids and Networks*. 2020; 24: 100402, https://www.scopus.com/authid/detail.uri?authorId=57209266879.
DOI: https://doi.org/10.1016/j.segan.2020.100402.

14. Tremblay, O. & Dessaint, L. A. "Experimental validation of a battery dynamic model for EV applications". *World Electric Vehicle Journal*. 2009; 3: 1–10. https://www.scopus.com/authid/detail.uri?authorId=7004406157. DOI: https://doi.org/10.3390/wevj3020289.

15. Vaideeswaran, V., Bhuvanesh, S. & Devasena, M. "Battery management systems for electric vehicles using lithium ion batteries". *2019 Innovations in Power and Advanced Computing Technologies.* Vellore: India. 2019. p. 1–9. https://www.scopus.com/authid/detail.uri?authorId=57208160489.
DOI https://doi.org/10.1109/i-PACT44901.2019.8959965.

16. Cleenwerck, R., Azaioud, H., Vafaeipour, M., Coosemans, T. & Desmet, J. "Impact assessment of electric vehicle charging in an AC and DC microgrid: A comparative study". *Energies.* 2023; 16: 3205, https://www.scopus.com/authid/detail.uri?authorId=57223800831.
DOI: https://doi.org/10.3390/en16073205.

17. Kouka, K., Masmoudi, A., Abdelkafi, A. & Krichen L. "Dynamic energy management of an electric vehicle charging station using photovoltaic power". *Sustainable Energy, Grids and Networks.* 2020; 24: 100402, https://www.scopus.com/authid/detail.uri?authorId=57209266879.
DOI: https://doi.org/10.1016/j.segan.2020.100402.

18. Cleenwerck, R., Azaioud, H., Vafaeipour, M., Coosemans, T. & Desmet, J. "Impact assessment of electric vehicle charging in an AC and DC microgrid: A comparative study". *Energies*. 2023; 16: 3205, https://www.scopus.com/authid/detail.uri?authorId=57223800831.
DOI: https://doi.org/10.3390/en16073205.

19. Pelletier, S., Jabali, O., Laporte, G. & Veneroni, M. "Battery degradation and behaviour for electric vehicles: Review and numerical analyses of several models". *Transp. Res. B: Methodol*. 2017; 103: 158–187, https://www.scopus.com/authid/detail.uri?authorId=57104781700.
DOI: https://doi.org/10.1016/j.trb.2017.01.020.

20. Negarestani, S, Fotuhi-Firuzabad, M., Rastegar, M. & Rajabi-Ghahnavieh, A."Optimal sizing of storage system in a fast charging station for plug-in hybrid electric vehicles". *IEEE Transactions on Transportation Electrification.* 2016; 2 (4): 443–453, https://www.scopus.com/authid/detail.uri?authorId=55212278600. DOI: https://doi.org/10.1109/TTE.2016.2559165.

21. Beal, L. D. R., Hill, D. C., Martin, R. A. & Hedengren, J. D. "GEKKO optimization suite". *Processes.* 2018; 6: 106. https://www.scopus.com/authid/detail.uri?authorId=57189381096.
DOI: https://doi.org/10.3390/pr6080106

22. "Photovoltaic geographical information system". – Available from: https://re.jrc.ec.europa.eu/pvg_tools/en/#HR. – [Accessed: Jul, 2022].

23. "DAM/IDM ANALYSIS" – Available from: https://www.oree.com.ua/index.php/IDM_graphs. – [Accessed: Jul, 2022]

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Оптимізація графіка диспетчеризації потужності зарядної станції на основі мікромережі з фотоелектричним модулем

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АНОТАЦІЯ

У світі взято курс на тотальну електрифікацію автомобілів. У недалекому майбутньому більшість авто будуть працювати на електрозаряді. Однією з головних причин невдоволеності користувачів електромобілями є нестача громадських зарядних станцій постійного струму. Оскільки зарядка електромобілів може спричинити додаткове зростання пікового навантаження на мережу, оптимальним рішенням є зарядні станції постійного струму з фотоелектричною генерацією з архітектурою мікромережі. Якщо зарядна станція має підключення до громадської мережі, тоді за умови оптимального використання сонячної енергії та системи зберігання можна збільшення прибуток агрегатора станції, завдяки продажу надлишкової енергії в мережу. В цій роботі проаналізовано звички клієнтів до заряджання на станціях постійного струму. Було виявлено, що пік попиту на зарядку спостерігається близько 9 та 14-17 годинами, в той самий час, коли припадає пікове навантаження на мережу. Таким чином, пік попиту на зарядку збігається з піковим навантаженням мережі та збільшує чистий пік системи. Однак цю надлишкову потребу в системі у формі зарядного навантаження можна задовольнити за допомогою встановленої сонячної фотоелектричної установки, оскільки вихідної потужності сонячної фотоелектричної енергії достатньо для задоволення потреб у зарядці в години пік сонячного випромінювання. Таким чином для розглянутої зарядної станції постійного струму було сформульовано оптимізаційну задачу dynamic economic dispatch, оскільки графіки генерації та навантаження змінюються в часі. Метою оптимізації є мінімізація вартості первинної енергії. Дану задачу, формалізовану як задачу змішаного цілочисельного лінійного програмування було розв'язано за допомогою розв'язувача interior-point solver бібліотеки GEKKO, на мові Python. Було опрацьовано чотири сценарії роботи станції, влітку та взимку, з фіксованим та динамічним тарифом на електроенергію. За результатами дослідження виявлено, що в умовах фіксованого тарифу влітку вартість первинної енергії можна зменшити в 2.5 рази, фактично збільшити прибуток, завдяки продажу електроенергії у громадську мережу. Взимку використання оптимізаційного алгоритму роботи станції забезпечить незначну економію коштів, що обумовлено низькою фотоелектричною генерацією. В умовах динамічного тарифу, який відповідає цінам на ринку на добу наперед, застосувавши оптимізаційний алгоритм було знайдено, що для даного експериментального варіанту роботи станції максимальний прибуток влітку складе 207,60 грн, взимку вартість первинної енергії складе 177,47 грн. Отримані результати свідчать про те, що робота зарядної станції за умови динамічних тарифів на ринку на добу наперед в Україні є перспективним напрямом розвитку зарядної інфраструктури в країні і доводить можливості ефективного використання відновлюваних енергоресурсів. Таким чином в цій роботі було проаналізовано світовий досвід розбудови зарядних станцій на основі мікромереж, інтеграція в них ВДЕ та підходи до побудови графіків диспетчеризації електроенергії. Також було досліджено фінансову спроможність роботи станції в умовах функціонування ринку електричної енергії в Україні.

Ключові слова: електромобілі; зарядна станція постійного струму; фотоелектрична генерація; мікромережа; графік диспетчеризації електроенергії; алгоритм змішаного цілочисельного лінійного програмування

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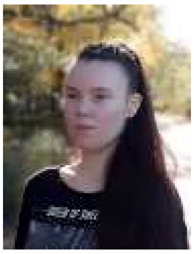

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