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Smart Sustainable Freight Transport for a City Multi-Floor Manufacturing Cluster: A Framework of the Energy Efficiency Monitoring of Electric Vehicle Fleet Charging

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Abstract: This study focuses on the problem of the efficient energy management of an independent fleet of freight electric vehicles (EVs) providing service to a city multi-floor manufacturing cluster (CMFMC) within a metropolis while considering the requirements of smart sustainable electromobility and the limitations of the power system. The energy efficiency monitoring system is considered an information support tool for the management process. An object-oriented formalization of monitoring information technology is proposed which has a block structure and contains three categories of classes (information acquisition, calculation algorithms, and control procedures). An example of the implementation of the class "Operation with the electrical grid" of information technology is presented. The planning of the freight EVs charging under power limits of the charging station (CS) was carried out using a situational algorithm based on a Fuzzy expert system. The situational algorithm provides for monitoring the charging of a freight EV at a charging station, taking into account the charge weight index (CWI) assigned to it. The optimization of the CS electrical load is carried out from the standpoint of minimizing electricity costs and ensuring the demand for EV charging without going beyond its limits. A computer simulation of the EV charging mode and the CS load was performed. The results of modeling the electrical grid and CS load using the proposed algorithm were compared with the results of modeling using a controlled charging algorithm with electrical grid limitations and an uncontrolled charging algorithm. The proposed approach provides a reduction in power consumption during peak hours of the electrical grid and charging of connected EVs for an on-demand state of charge (SOC).

Keywords: city multi-floor manufacturing cluster; smart sustainable city; electric vehicle fleet; smart energy management; energy efficiency monitoring; state of charge; electrical load profile

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1. Introduction

The development of the megapolis is associated with the creation of smart, sustainable city multi-floor manufacturing clusters (CMFMCs) to meet the needs of the local population and businesses for daily goods and related services in a timely manner. The CMFMCs are located directly in residential areas of the megapolis and include a group of multi-floor manufacturing buildings and a city logistics node (CLN) through which materials, products, and goods are delivered to suppliers and customers [1–3]. Independent fleets of trucks implement both internal (intra-cluster cargo transportation) and external (cargo transportation outside the cluster) material flows [4]. For the implementation of internal material flows in the CMFMC, an independent fleet is used, mainly a number of light freight electric vehicles (EVs), while for the implementation of external material flows, independent fleets with a wider range of trucks can be used [5–7]. The use of independent fleets of freight EVs implies a rational use of energy resources in the megapolis [8–11]. In the modern conditions of climate change and depletion of fossil energy resources, the issues of decarbonization, energy efficiency, and reduction in final energy consumption in city manufacturing are among the most promising [12–16]. Energy efficiency is considered a way to solve the problem of a "dependence on energy imports and scarce energy resources, as well as the need to limit climate change" [17] and search for "a cost-effective balance between decarbonizing energy supplies and reducing final energy consumption" [18].

In accordance with the Paris Agreement on Climate Change, the European Union has set a goal to reduce greenhouse gas emissions by 40% by 2030 [19]. The pursuit of this goal contributes not only to solving the problem of global warming but also to improving air quality, especially in megapolises, which will have a beneficial effect on the health of residents. The use of clean energy and renewable sources of electricity, increasing energy efficiency, and reducing final energy consumption are considered tools to achieve this goal [20,21]. In the process of reducing greenhouse gas emissions through the transition to a low-carbon economy, an important role is assigned to the decarbonization of the transport sector through the use of clean vehicles and the development of electromobility [22–24]. At the same time, the mass introduction of EVs requires the development of charging station (CS) infrastructure. In turn, the consumer demand for the independent fleets of freight EVs determines the nature of the CS's load schedule and the efficiency of their integration into the electrical grid. The intensive development of CSs and the increased impact of their load on the electrical grid contributes to the implementation of strategies for managing the charging of the freight EVs in consideration of electricity costs under limited power distribution [25,26]. The development of bi-directional charging technology (Vehicle-to-grid—V2G) makes it possible to use EVs not only to align the electrical load schedule of the power system (using controlled charging technology) but also as energy storage devices from solar power plants and energy sources to cover peak loads, as well as using strategies for managing the charging/discharging of freight EV batteries to regulate frequency and maintain voltage while taking into account battery degradation [27,28]. Thus, the structure of the fleet and the cycle of movement of freight EVs, the charging strategy, and the mode of CS operation have a significant impact on the efficiency of the functioning of the power system and electric grids. The CMFMCs provide charging for their independent fleet of the freight EVs during hours when electricity is cheaper and sells electricity to the electrical grid during hours when CS usage is low. This strengthens the role of an independent fleet of freight EVs in managing the demand for electricity, not only as an active consumer of electricity, but also as a participant in the energy market. Therefore, in the current conditions of the energy transition to a low-carbon economy, EVs are considered a way to achieve sustainable energy in smart cities.

The CMFMCs have CSs for servicing independent fleets of freight EVs and buy electricity on the energy market. Thus, each freight EV should be considered as the final energy consumer, so it is important to consider the energy efficiency issues of its operation [22]. The solution requires an analysis of the energy efficiency of the independent fleet of EVs and the efficiency of the organization of cargo transportation, as well as the operating mode of the CS, to identify the causes of inefficient uses of electricity and decision making in the smart sustainable development of electromobility and the efficiency of local electric grids and the power system as a whole. Thus, it is necessary to consider all aspects of the problem of decarbonization of the transport sector and the development of electromobility to ensure monitoring of all its components for the energy-efficient operation of the independent fleet of freight EVs within each of the CMFMC and megapolis. It should be noted that to solve the formulated problems, a smart energy management system (SEMS) is used, the implementation of which is an important tool for improving energy efficiency and reducing final energy consumption by an independent fleet of freight EVs within each of the CMFMC and megapolis as a whole [29].

The main contributions of this study are summarized as follows:

1. The issues of the SEMS within the CMFMC were studied to ensure the efficient energy consumption of an independent fleet of freight EVs and improvement of electrical grid sustainability.

2. The architecture of information technology for the integrated monitoring of the energy efficiency of an independent fleet of EVs is proposed and contains three categories of classes, combined with procedures for obtaining information, calculation algorithms and methods, and control procedures.

3. The solution to the tasks of monitoring the CS operation mode from the standpoint of minimizing electricity costs and ensuring the demand for charging EV batteries without going beyond the limits of restrictions is demonstrated. This approach to the charging strategy is applicable for both battery EVs (BEVs) and plug-in hybrid vehicles (PHEVs).

4. The effectiveness of the proposed technique is confirmed by the results of modeling based on experimental data.

The rest of the paper is organized as follows: Section 2 provides the literature review of SEMSs; Section 3 presents the SEMS within the CMFMC and describes the principles and methodology of information support for monitoring the energy efficiency of the independent fleet of freight EVs; Section 4 contains the description of the initial data and displays the results of developing a model for optimizing the operating mode of the CSs and assessing their activities based on the implementation of operation monitoring; and the last section is devoted to discussions and conclusions.

2. Literature Review

2.1. EMS and Its Role in Energy Consumption Management for Sustainable Development

Strengthening the role and importance of efficient resource and energy use prioritizes increasing the efficiency of the managing process of energy consumption [30]. The main goal of energy management within the CMFMC is to achieve a high level of energy efficiency management while simultaneously using all resources rationally. The problem of energy management is holistic and requires consideration of both explicit and hidden cause-and-effect relationships.

A key element of effective energy management are approaches aimed at the implementation of SEMS designed to improve energy performance and increase energy efficiency [29,31]. The importance and effectiveness of the implementation of SEMS for analyzing the usefulness of procedures and actions aimed at improving energy efficiency have been proven in many studies [32–39]. At the same time, it has been noted that the introduction of SEMS provides not only a reduction in energy consumption [29,34,40] but also an improvement in production productivity and competitiveness of CMFMC [7,35,37,41]; it promotes the transition to sustainable energy [30] and has a beneficial effect on sustainable development [39], in particular: the quality of products or services, environmental indicators [38,42], occupational health and safety [36], etc.

The SEMS should be considered as a complex of organizational and technical means and software as well as methodological support which together make it possible to organize and manage cargo transportation in such a way to ensure the minimum consumption of energy resources and the optimization of energy costs. At the same time, it is necessary to consider the specifics of the work of the research object, that is, an independent fleet of freight EVs within the CMFMC, as well as the interests of the power system and consumers of the services provided [6,8,9].

2.2. The Role of Energy Efficiency Monitoring in SEMS

In general, monitoring is interpreted as a system of measures for observation and control which are carried out in a certain way to assess the condition of the object of study and analyze ongoing processes to quickly identify trends in its changes. Energy monitoring is considered a set of measures (observations, estimates, and forecasts) that allow for continuous monitoring of the mode of fuel consumption and energy resources in the technical system, registering its main indicators, and promptly identifying the results of the impact of external and internal factors on the energy consumption efficiency.

According to the ISO 50001 standard, energy efficiency monitoring is a mandatory component of SEMS [29]. It is based on the collection of information about the object of study and is aimed at verifying compliance with energy consumption modes, the implementation of planned activities and operating modes, and compliance with the established values of energy indicators. Data analysis obtained from the monitoring system helps to identify cyclical changes in the operating conditions of the object of study due to the influence of external (social or climatic) factors as well as a formalized description of typical operating conditions [43]. The systematization of the received information allows for a prompt response to changes in the operating conditions of the facility and adjusts the technological process to ensure the efficient use of natural and energy resources. That is, the availability of the necessary information that meets the requirements of completeness, reliability, and timeliness provides an opportunity to effectively plan and control technological processes and energy consumption [44]. Thus, energy efficiency monitoring should be considered as a component of management activities that involves monitoring the state, parameters, and characteristics of the object of study in order to form an information base for analyzing and evaluating the development of trends in energy consumption and preparing and making informed management decisions.

2.3. Principles of SEMS

In modern conditions, any object (process; enterprise; technological, energy, transport system; CMFMC; and megapolis as a whole) which contains a large number of functionally interconnected structural elements that consume energy and/or natural resources, each of which has its own characteristics of functioning, should be considered as a complex system. The effectiveness of the functioning of such a system depends on many factors and requires a comprehensive consideration of information of a different nature from different sources. This requires monitoring the efficiency of not only energy consumption but also the technological processes of the object of study and influencing internal and external factors, not just as a data collection system but as a component of information support for decision-making.

In this regard, ensuring an increase in the level of operational efficiency of a complex system should be based on the principles of smart management. The smart management strategy of any complex system provides for the integration of information on all operation indicators and influencing factors in a single database based on the use of cloud technologies; systems for the accumulation, storage, and processing of information; data mining; planning; and control of technological, energy, and economic parameters as well as intelligent feedback and decision-making.

The development of Industry 4.0 contributes to the implementation of SEMS to ensure a high level of energy efficiency. Digitalization of city manufacturing and the introduction of big data analysis technologies, machine learning, and Internet of Things (IoT) technologies make it possible to provide two-way communication between energy consumption and generation devices, the electrical grid, sensors of technological parameters, systems for monitoring and accounting for energy consumption, etc. and optimal planning of the technological process, consumption of energy resources, and the response of the energy system to demand on the consumer side. Therefore, the introduction of information and communication technologies for SEMS in various fields is gaining increasing interest from researchers. The SEMS in smart sustainable CMFMC offer approaches to applying the capabilities of Industry 4.0 to monitor energy consumption for various applications [45]. These approaches involve data collection using smart meters and Supervisory Control and Data Acquisition (SCADA) systems, database generation and information storage, and the use of database machine learning methods to predict energy consumption. Pawar et al. [46]

emphasized the importance of SEMS for the efficient use of renewable sources and propose a controlled algorithm based on the hourly planning of energy consumption, and for the day ahead, the use of IoT technology for energy consumption monitoring. The IoT technology and smart meters are considered the main resources of the SEMS which implement the aggregation, use, and analysis of data for effective energy management [47]. It is also of interest to use IoT technology in SEMS in response to electricity demand in the electrical grid, which provides an aggregation of electrical load and existing Internet connections for sustainable management of the electric power system [48]. Dongbaare et al. [49] considered the operation issues of SEMS for the domestic sector and proposed an algorithm for monitoring and managing the energy consumption of household appliances, considering the limitation of heavy loads during peak hours, and the availability of renewable energy sources. The SEMS is used in a smart home that is powered by a renewable energy grid, considering the bidirectional energy flow. The control process minimizes daily operating costs and is based on optimal planning of energy resources and electrical load, the model of which is based on a genetic algorithm [50].

In modern conditions, the implementation of SEMS requires the use of information technology to integrate the control and management of technological processes and energy consumption, and consider the methods of managing the operating modes of the electric power system. Thus, the SEMS at any modern facility should be considered a computer information and analytical system based on the use of intelligent systems for collecting, storing, processing, and analyzing data, providing for the comprehensive monitoring (i.e., measurement, observation, analysis, planning, and control) of all components of the efficient operation of the facility and ensuring the optimization of energy consumption, reduction in energy costs, sustainable operation of the energy system, and reduction in CO_2 emissions.

3. Materials and Methods

3.1. SEMS for Independent Fleet of Freight EVs within the CMFMC

Figure 1 shows the CMFMC with CLN and other logistics facilities in the structure of a megapolis [2,3]. The CLNs within the megapolis interact with the production buildings of the corresponding CMFMCs, between themselves, other logistics facilities, suppliers, and customers by a delivery service platform (DSP) [2]. The CLNs and other logistics facilities such as city logistics centers (CLCEs), city waste transfer stations (CWTSs), megapolis logistics nodes (MLNs), megapolis distribution logistics hubs (MDLHs), megapolis transportation logistics hubs (MTLHs), and megapolis waste transfer stations (MWTSs) are equipped with CSs in order to combine the loading-unloading operations and charging of the freight EVs [2,51].

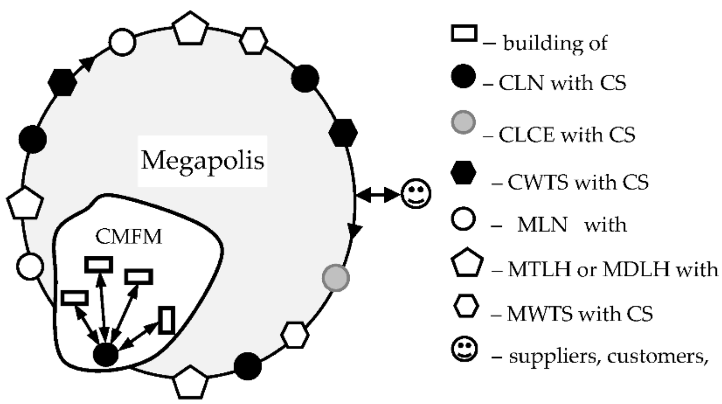

Figure 1. CMFMC with CLN and other logistics facilities in the structure of a megapolis.

Ensuring a high level of energy-efficient operation of the independent fleet of freight EVs within the CMFMC and the efficiency of their integration into the electrical grid, considering the concept of the sustainable electromobility and energy industry, requires considering many factors that can be represented by the following groups:

1. Technical group—involves an analysis of the state of the independent fleet of freight EVs, their characteristics, and a comparative analysis of the efficiency of using different EVs for cargo transportation.
2. Logistics group—involves considering requests for volumes, destinations, and time of cargo delivery, planning and optimizing the route of cargo delivery, and the freight EVs movement considering urban traffic.
3. Energy group—involves planning the electricity consumption by the EVs for cargo transportation, the amount of electricity consumption by the independent fleet, the charging mode of freight EVs, and the creation of a charging profile (charging scenarios considering technical limitations, including the power system) as well as assessing the residual charge of the EV battery and the possibility of electricity supply to the electrical grid during hours of maximum electrical load. In the case of a CS power supply from a local electrical grid with sources of distributed generation (wind or solar power plants), the issue of planning the amount of electricity generation from these sources and charging EVs to use them as electricity storage devices for the electrical grid then becomes relevant.
4. Economic group—involves assessing the efficiency of cargo transportation, considering the costs of their implementation, including electricity costs, assessment of the charging mode efficiency of freight EVs, and considering electricity prices at different hours of the day.

It should be noted that each group is a set number of tasks. At the same time, to solve each of the tasks, it is necessary to develop and use different approaches and methods as there are both explicit and implicit causal relationships between the components of different groups. The implementation of SEMS within the CMFMC provides for the identification of these relationships, their assessment, and joint consideration of their impact not only to solve the problem of minimizing the costs of cargo transportation but also to ensure the sustainable electromobility and energy industry. The implementation of joint accounting of various components requires the organization of comprehensive monitoring of the energy-efficient operation of the independent fleet of freight EVs and its information support system.

3.2. Information Support for Integrated Monitoring

A monitoring information system is a system of specially organized tracking of the state and behavior of the control object, and the external environment according to agreed criteria or indicators to determine the compliance of their actual and planned values. This is a system for collecting and accumulating data (the amount of energy consumed, the main characteristics of technical, technological, operational, and external factors affecting energy consumption) in order to obtain operational information and analyze it to improve energy efficiency and minimize energy costs. These indicators can be used as input data in complex models of analysis and forecasting to form a comprehensive assessment of the state of the control object, improving the operation efficiency.

The operation efficiency of the independent fleet of freight EVs within the CMFMC as an object of management is a complex dynamic system characterized by a large amount of information, the presence of information links between the objects of the subject area, and the need for regular information exchange. To solve the problem of energy efficiency monitoring, the first step is to obtain information and form a database characterizing the state, conditions, and operation efficiency of the independent fleet of freight EVs, and the state of the environment.

The use of an object-oriented approach simplifies the description of the components of the energy efficiency problem under consideration of the independent fleet of freight EVs within the CMFMC and the corresponding procedures and algorithms, but retains their subordination to a single goal. That is, all subsystems of control objects, regardless of their operation, are united by a single information space. The result of this operation is the formation of a unified knowledge base for decision making to improve the energy efficiency of the independent fleet of freight EVs within the CMFMC.

Web-oriented monitoring systems are considered an effective tool for the information support of SEMS [52]. Therefore, the information system for integrated monitoring of the energy efficiency of the independent fleet of freight EVs is focused on the use of web technologies, that is, the formation of database and data warehouses, components for collecting, evaluating, and intelligent processing of information as well as visualization of the results of its processing for management decision making.

The structure of the information system of energy efficiency monitoring is a set of complex subsystems. The data collection, pre-processing, and storage module receives information flows from various sources and converts them into formats convenient for storing and post-processing data. The information accumulation subsystem involves the integration of physical devices for recording primary data. Information sources are sensors as well as devices which control and measure energy consumption accounting systems, traffic control and electric vehicle control, urban traffic control, and logistics system of cargo transportation, as well as systems for monitoring the parameters of the electrical grid and distributed generation sources (if such sources are provided in the local electrical grid). The presence of automated control systems and the use of ZigBee wireless data transmission simplifies the collection and processing of information. The subsystem provides the collection of monitoring data from local measurement subsystems and weather stations, their verification and transmission to the central web server of the CMFMC (or the CLN), and their placement in the database. The database in the energy efficiency monitoring system of the independent fleet of freight EVs is an integrated set of specially structured data and links between them. The data warehouse provides a unified logical representation of technical, logistical, energy, climate, and other data contained in the database. In the data warehouse, along with the current data, retrospective data is stored with a record of the time to which they relate.

The use of WEB technologies and ZigBee wireless data transmission technology provides communication and data exchange between control points and the central server within the CMFMC which ensures data consolidation into a single information database. The monitoring results are the knowledge base for the implementation of management actions to improve the operation energy efficiency of the independent fleet of freight EVs within the CMFMC and its integration into the electrical grid. Monitoring information is presented in a processed form which is the result of the interaction of a set of actions (collection, systematization, data processing, and reporting in convenient formats), and is accessible to dispatchers and energy managers of the CLN and CMFMC.

3.3. Object-Oriented Formalization of Information Technology for Integrated Energy Efficiency Monitoring of the Independent Fleet of Freight EVs within the CMFMC

The architecture of modern information systems must comply with the policy of innovative development, regardless of the scope of their use. The main requirements for the functionality of the information system are as follows: the openness of the system structure, the availability of a flexible mechanism for introducing new objects and algorithms for solving problems, and the ability to adapt to changes in the structure or values of the parameters of the objects in the subject area. Therefore, the creation of the information monitoring system as a single automated system for storing, searching, displaying, and analyzing data is based on the principles of modularity.

An object-oriented approach was used to formalize the process of integrated monitoring of the energy efficiency operation of the independent fleet of freight EVs within the CMFMC [53]. Its main approach is the decomposition of the problem into separate conceptual classes. For this purpose, an objective analysis of the subject area was carried out taking into account the tasks of the SEMS of the freight EVs of CMFMC. As a result, the entities of the subject area are presented in the form of information objects interacting with each other (Figure 2) for the implementation of subsequent object-oriented design.

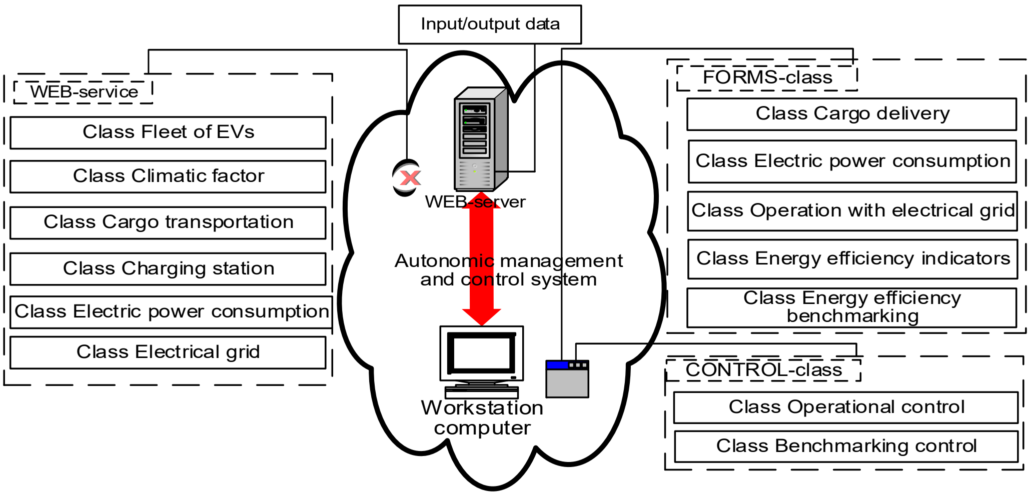

Figure 2. The architecture of information technology for the integrated energy-efficient monitoring of an independent fleet of freight EVs within the CMFMC.

In the architecture of information technology for integrated energy-efficient monitoring of the independent fleet of freight EVs within the CMFMC, the following class categories are identified:

1. WEB-service—a set of classes integrated by the procedure for obtaining initial information about the object of study (technical characteristics of the independent fleet of freight EVs: load capacity, battery power, power reserve, etc.; characteristics of cargo transportation: volume, time, route of cargo delivery, speed of movement, etc.; climatic factors; CS operating mode indicators; electrical grid indicators: electrical load, power reserve, electricity tariffs, power consumption, etc.).
2. FORMS-class is a set of classes associated with computational algorithms and models, providing the following procedures:
   - "Cargo delivery" class—provides for sub-class "Delivery route" (description, analysis, and optimization of the route of cargo delivery, detection and identification of cyclical changes in demand for cargo transportation); sub-class "Electric vehicle operation mode" (formalized description of cargo transportation for typical operating conditions; adjustment of the cargo transportation characteristics and its route, taking into account cyclical changes in demand; planning energy-efficient modes of operation for the independent fleet of freight EVs within the CMFMC).
   - "Electric power consumption" class—provides for sub-class "Electric power consumption of freight EV" (power consumption models for EVs of different types taking into account climatic factors; determination of the basic level of electric consumption for EVs of different types); sub-class "Electric power consumption of the independent fleet of freight EVs within the CMFMC" (power consumption models considering cyclical changes in demand; determination of the basic level of power consumption for typical work conditions).
   - "Operation with electrical grid" class—provides for: sub-class "EV charging" (formation of the freight EV charging profile considering the characteristics of the battery and its operating schedule); sub-class "Charging mode of the independent fleet of freight EVs within the CMFMC" (planning of the charging schedule of freight EVs considering their operation schedules, formation of the charging profile of the the independent fleet of freight EVs within the CMFMC); sub-class "Electric grid load" (optimization of electric power consumption of the freight

EVs connected to CS; CS load profile planning); sub-class “Discharge mode of the independent fleet of freight EVs within the CMFMC” (determination of the amount of electricity to be generated by EVs into the electric grid, considering the remaining battery charge, planning the schedule of the independent fleet of freight EVs to the electric grid, and considering their operation schedules); sub-class “Generation of electricity from renewable energy sources” (determination of the volume of electricity generation from renewable energy sources considering climatic factors, formation of a profile of electricity generation from renewable energy sources, and formation of a CS load profile on the electric grid considering the profile of electricity generation from renewable energy sources).

- “Energy efficiency indicators” class—provides for sub-class “Energy efficiency indicators of the independent fleet of freight EVs” (determination of the energy efficiency coefficients of the independent fleet of freight EVs within the CMFMC participating in cargo transportation, and the coefficient that considers the level of EV battery degradation); sub-class “Indicators of energy efficiency of cargo transportation” (determination of coefficients of energy efficiency of cargo transportation within the CMFMC); sub-class “CS energy efficiency indicators” (determination of the energy efficiency coefficients of CS operating modes within the CMFMC).
- “Energy efficiency benchmarking” class—provides for sub-class “Energy efficiency of freight EVs” (comparative analysis (internal and external) and assessment of the level of energy efficiency of the independent fleet of freight EVs within the CMFMC participating in cargo transportation; setting tasks for its improvement); sub-class “Energy efficiency of cargo transportation” (comparative analysis (internal and external) and assessment of the level of energy efficiency of cargo transportation within the CMFMC; establishment tasks for improvement).

3. The control class is a set of classes associated with procedures for monitoring the energy-efficient operation of the independent fleet of freight EVs. Provides the following procedures:
   - “Operational control” class—provides for sub-class “Control of electrical consumption” (control of the efficiency of electrical consumption of freight EVs, considering their operation schedule and the independent fleet of freight EVs within the CMFMC, identification of moments of non-accidental reduction (increase) in the efficiency of electrical consumption, and signaling the exceeding of planned values for independent fleet electrical consumption); sub-class “Control of cargo transportation” (control of characteristics of cargo transportation and identification of reasons for non-compliance with planned values power consumption); sub-class “Control of energy efficiency indicators” (control of operation energy efficiency indicators of the independent fleet of freight EVs and the dynamics of specific power consumption to identify trends in increasing/decreasing the level of energy efficiency); sub-class “Control of electrical grid operation” (control of the CS electrical load profile).
   - “Benchmarking control” class– provides for sub-class “Control of energy efficiency indicators” (analysis of the dynamics of the energy efficiency level of the independent fleet of freight EVs within the CMFMC, analysis of the dynamics of energy efficiency indicators of freight EVs); sub-class “Control of cargo transportation” (analysis of the dynamics of energy efficiency indicators of cargo transportation).

Each class has a specific data structure (class properties) and rules for its implementation (class methods—calculation algorithms, procedures, and communications that ensure the class operation), access to object data, methods to process them, and operations to perform to solve the problem. The implementation of each class provides for the sequential execution of several procedures. The result is information that is aggregated in the database and knowledge base. Some of the information is the source for subsequent procedures for planning and monitoring the EVs operation mode or energy consumption, and another part is used to make a decision on improving the energy-efficient operation of the independent fleet of freight EVs within the CMFMC.

3.4. Monitoring of CS Operation Mode and Its Impact on the Load of the Electrical Grid

A large number of EVs requiring simultaneous charging provide an additional electrical load, and daytime charging can cause an overload of the electrical grid [54]. In order to avoid peak demand for electricity used to charge freight EVs, it is necessary to plan the charging process and coordinate the CS operation mode with the electrical grid.

The organization of the CS operation mode and the charging profile of the independent fleet of freight EVs within the CMFMC should be carried out from the standpoint of an active consumer. With this approach, the target functions of CS operation control are the optimization of power consumption within the CMFMC, optimization of the load mode of the electrical grid, reduction in peak loads, and alignment of the load schedule of the power system.

Most solutions to the problem of charging a large number of EVs are based on various types of planning and creating of their charging profile—charging scenarios with technical limitations. These restrictions depend on the situation of the CS (the number of EVs, their charging level, the possibility of simultaneous maintenance, and the stated charging time). The charging period within the CMMS is convenient for each freight EV and the grid load schedule may conflict [55]. The batteries of EVs may be charged using onboard chargers connected to CSs in conditions of limited connection power. Thus, the real-time charging management system of the cargo fleet should provide each EV with guaranteed charging in conditions of limited energy consumption.

One of the approaches contributing to ensuring guaranteed charging of EVs is the situational algorithm [56] which allows real-time monitoring of the charging process and responding to changes in power consumption. The approach is based on a Fuzzy expert system that evaluates each situation by giving each EV a priority for connection to the CS, and considers the charge weight index (CWI) of its battery.

The operation of the situational algorithm involves the execution of several successive steps [56]: calculation of the required energy for charging to a given level; determination of the CWI (performed in a Fuzzy expert system); calculation of the actual charge level consumed by each EV; the total demand for electricity at the end of the specified polling period of the controller; and selection of the maximum number of EVs with the highest CWI, so as not to violate the restrictions from the power supply company.

The CWI depends on the energy required for charging, the required charging power, and the available charging time (parking time of the electric vehicle) [57]. The membership function (MF) of CWI is formed by the MFs of the input variables [56]:

$$\begin{aligned} &f : W_{req_i}, P_{ac_i}, t_{parking_i} \rightarrow CWI_i \\ &\mu(W_{req_i}), \mu(P_{ac_i}), \mu(CWI_i) \end{aligned} \tag{1}$$

The calculation of the CWI of the charge is carried out considering fuzzy logical rules [56]. When the battery reaches the required charge level, the CWI of this EV will be zero.

All decision-making factors are determined based on the data provided to the aggregator via the intelligent panel [57]. The owner of the EV indicates the battery capacity of the EV, and the required and initial battery charge levels in %. This information is sent to the controller of the CS. The implementation of the algorithm is made in the form of m-files, launched with a model update frequency—once every T minutes. With the same frequency, the charging controller receives information about the battery level of the EV. The result of the expert system operation is a decision to allow charging of the largest number of EVs, taking into account their CWI priority, the limitations of the power supply company, and the possibility of ensuring guaranteed charging of these EVs. At the same time, the charging strategy considers the optimal charging current, considering the battery level of a particular freight EV, in order to extend the battery life.

The modern technologies for the development of the "smart electrical grid" and SEMS are based on a number of technological capabilities, including network analytics, automated reading of meters, remote monitoring, control of mobile working devices, and the use of SCADA systems operating via the Internet Protocol. This facilitates our use of the information and communication capabilities for a two-way interaction with the technological and commercial infrastructure of the power system through intelligent metering in the remote load control mode and independent consumer response, taking into account the electricity tariff. The ability of the control subject to measure and observe the behavior of the control object is fundamental.

In order to ensure the interaction of a CS as an active consumer and an energy company, it is necessary to implement the CS operation monitoring system. Such monitoring provides for the joint solution of a number of tasks: monitoring the charging process of the EVs connected to CS, monitoring the load created by CS on the electrical grid, and minimizing power consumption and electricity costs.

The situational algorithm for controlling the freight EVs charging is used to optimize power consumption and minimize electricity costs within the CMFMC. The methodology for modeling the CS operations is based on considering the priority of an EV to decide about the charging permission/prohibition, and the limitations of the power system and the current tariff. To implement the situational algorithm, a MATLAB Simulink model of a typical electrical grid with a CS and a residential load has been developed which can be scaled to the required dimensions of the power grid under study.

4. Results

This section provides an example of the implementation of CS monitoring tasks corresponding to the class "Operation with the electrical grid" (sub-class "EV charging"; sub-class "EV fleet charging mode"; sub-class "Electrical grid load") of the FORMS-class category of the proposed information technology for the integrated energy efficiency monitoring of the independent fleet of freight EVs within the CMFMC. The solution to the problem is carried out from the standpoint of minimizing electricity costs and ensuring the demand for charging EV batteries without going beyond the limits of restrictions. The purpose of the proposed approach is to increase the efficiency of CS power consumption.

4.1. Analysis of Experimental Data

The formation of the CS mode control algorithm is based on the characteristics of the EV battery charging processes. A simplified equivalent schematic diagram of an EV battery is shown in Figure 3 [58]. According to the scheme, the following values are required for monitoring: charge power, charge process profile, charge level change, battery voltage, current, and energy conversion efficiency of the charger.

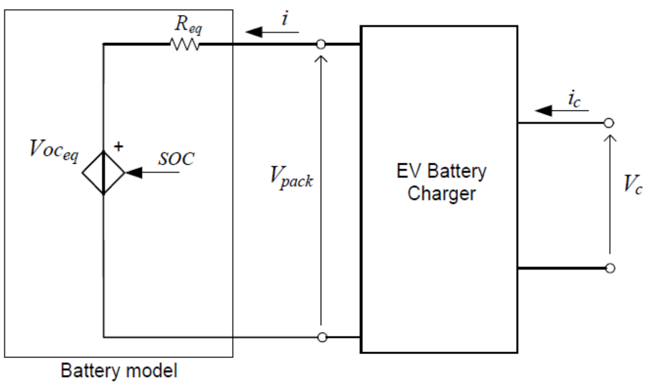

Figure 3. Simple schematic diagram of an EV battery.

The battery model of an EV consists of a controlled source of equivalent voltage and equivalent resistance [58]. The voltage at the battery terminals is defined as:

$$V_{pack} = V_{OCeq} + R_{eq} \cdot i \tag{2}$$

The state of charge (SOC) of the battery during charging is calculated as:

$$\begin{aligned} SOC(j) &= \sum_{k=1}^{N_c} \frac{dQ(j)}{Q_{bat}} + SOC_{start}, \\ dQ(j) &= i(j) \cdot T \end{aligned} \tag{3}$$

The power on the battery side and the electrical grid are calculated according to the equations [59]:

$$\begin{aligned} P_{dc} &= V_{pack} \cdot i \\ P_{ac} &= V_c \cdot i_c \end{aligned} \tag{4}$$

Power is also the SOS function, so (3) can be rewritten as:

$$\begin{aligned} P_{dc}(SOC) &= V_{pack}(SOC) \cdot i \\ P_{ac}(SOC) &= V_c \cdot i_c(SOC) \end{aligned} \tag{5}$$

The power on the electrical grid is kept constant during charging and considering the efficiency of the charger:

$$P_{ac} = \frac{P_{dc}}{\eta}, \tag{6}$$

from (4) and (5), can be written as:

$$i(SOC) = \eta \cdot \frac{V_c \cdot i_c}{V_{pack}(SOC)}. \tag{7}$$

The battery is charged by the simplest CC/CV method. CC/CV is the most widely used method in practice due to its simplicity of implementation. A constant current is applied to the battery in the first step. When the battery voltage reaches the set value, the voltage will be kept constant, and the current will decrease exponentially until charging is completed [60]. A typical curve of voltage and current changes during CC/CV charging is shown in Figure 4.

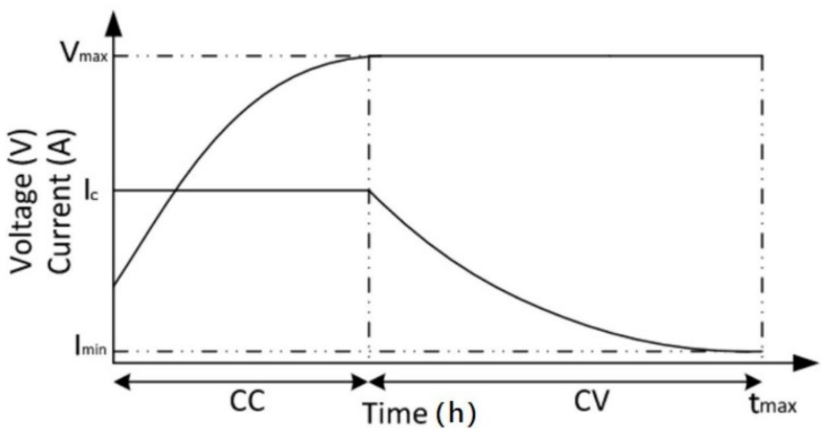

Figure 4. Charging stages of Li-ion charging CC/CV.

As shown in Figure 4, the constant current (CC) charging mode ends when the voltage reaches Vmax. The charging process, as mentioned earlier, ends when the current drops to a predetermined level. After changing the mode to constant voltage (CV), the charge takes longer. However, this is done to prolong battery life and prevent overheating by recharging with less current. For example, the charge level of a lithium-ion battery is limited from 20% to 90% [61]. Charging is done with constant current (CC) on the battery side up to 80% of the state of charge and then constant voltage (CV) up to 100% SOC.

The brushless CC motor of the experimental EV is powered by 16 Li-ion batteries (InnoPOWER-LFMP40AH) with a nominal capacity of 40 Ah. The lithium-ion battery is the most popular battery chemistry used in EVs. The technical parameters of the battery are given in Table 1 [62]

Table 1. Technical characteristics of the EV battery.

Electrical Properties	Value
Power, P_{nom}	2 kW
Rated capacity, Q_n	40 Ah
Nominal Voltage, U_n	51.2 V
Charging Voltage, U_c	58.4 V
Max discharging Voltage, U_d	44.8 V
Average charging current (0.5 C), I_c	20 A
Standard Charging Current (0.3–1.0 C), I_j	12–40 A

The battery is discharged at a load of 20 A (0.5S) when using direct current electrical load ITECH. The battery is charged with a constant (direct) current (CC) of 15 A until the SOC is about 90% and the maximum cell voltage is reached [59].

The charger is a single-phase uncontrolled charger JIARUI RB 900. The technical characteristics of the charger are given in Table 2.

Table 2. Technical characteristics of the charger.

Electrical Properties	Value
AC Input	
Voltage, V	180–240
Current, A	7
DC Output	
Voltage, V	58.4
Current, A	15

The precision power analyzer ZES ZIMMER LMG500 was used for measurement and registration. The impact of the charging load directly on the grid was measured using the MAS application for the LMG500. The InnoPOWER-LFMP40AH Li-ion battery charging takes 3 h and consists of three steps: the beginning of charging (the current consumed by the battery of the EV rapidly increases); the main charge period (CC); and the end of charging (the charging current decreases slowly). The load graph shown in Figure 5 was taken as a basis for calculating the load from the battery charging of the EV.

4.2. Development of the CS Mode Optimization Model

The CS model optimization in this study will depend on the price of time-of-use electricity. The price divides the tariff into three main blocks: night dips, half-peak, and peak prices (Figure 6) [63].

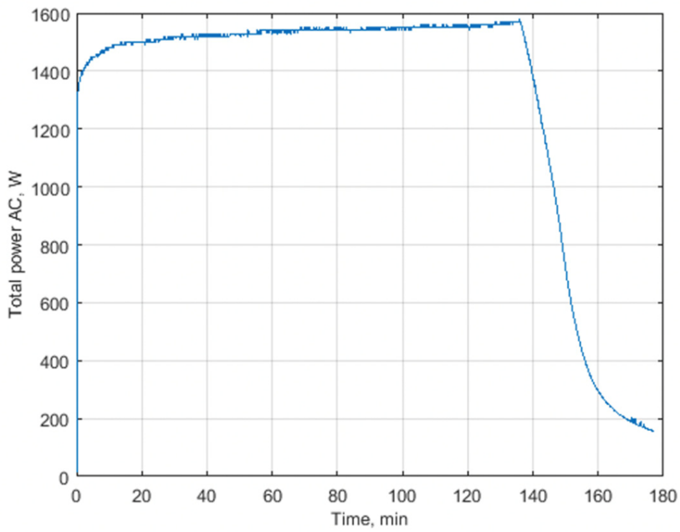

Figure 5. Load graph when charging on the alternating current side.

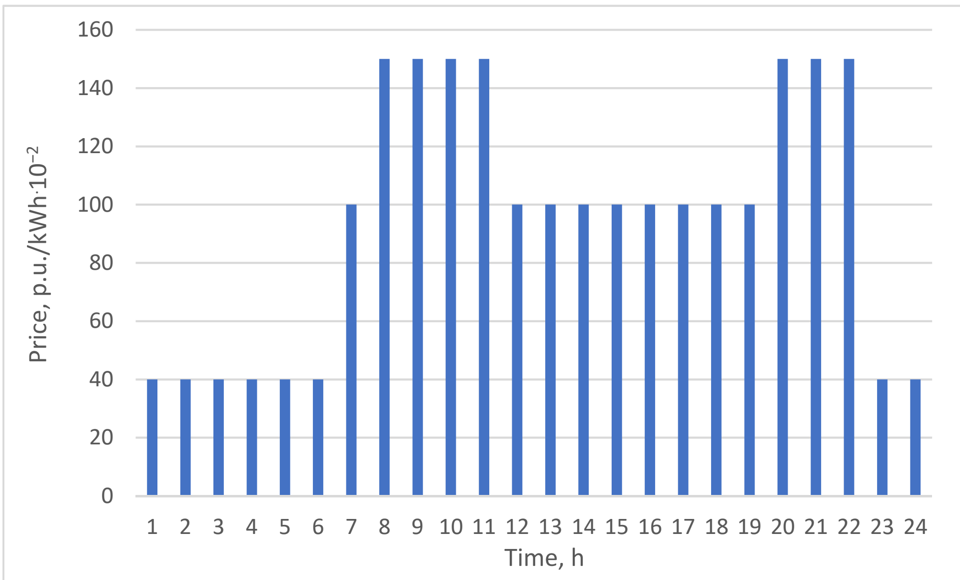

Figure 6. Structure of the electricity tariff.

The cost optimization for intelligent charging should be achieved by solving the linear optimization programming problem [64]:

$$\sum_{l=1}^{N_d} C(t_l) \cdot P_s(t_l) \to \min. \tag{8}$$

At the same time, at each moment of time, limitations are considered related to ensuring the permissible deviation of the mains voltage and current and the limitations on the electrical grid's load:

$$\begin{aligned} & V_c^{\min} < V_c(t_l) < V_c^{\max} \\ & I(t_l) \leq I_{\max} \\ & P_s(t_l) + P_L(t_l) \leq P_s^{\max} \\ & l \in (0; N_d) \end{aligned} \tag{9}$$

The power consumed for charging over time depends on the number of freight EVs being charged:

$$P_s(t) = f[x(t)], \tag{10}$$

The problem of optimizing the cost of charging involves considering the task of minimizing energy consumption, which can be represented as [65]:

$$P_S(t) = \sum_{l=1}^{N_d} P_S(t_l) = \sum_{l=1}^{N_d} \sum_{g=1}^{N} \sum_{j=1}^{N_c} P_{j,g} \cdot F\left(P_{j,g}, t_l\right) \to \min \tag{11}$$

Limitations, considering the start of charging (including the possibility of starting charging on the previous day) and its duration according to [65], as well as the need to ensure charging of all connected EVs:

$$F(P_j, t_l) = \begin{cases} \sum\limits_{k=1}^{l} f(t_k) h(SOC_{j-(l-k)}), N_c \le k \le N_d, l-k < j \\ \sum\limits_{k=1}^{l} f(t_k) h(SOC_{j-(l-k)}) + \sum\limits_{k=N_d-(N_c-l)}^{N_d} f(t_k) h(SOC_{j-(l+N_d-k)}), 1 \le l \le N_c, l-k < j, l+N_d-k < j \end{cases} \tag{12}$$

$$\sum_{g=1}^{N} x_g(t) = 100\% \tag{13}$$

Figure 7 shows the structure of intelligent charging control of the EV considering electricity tariffs.

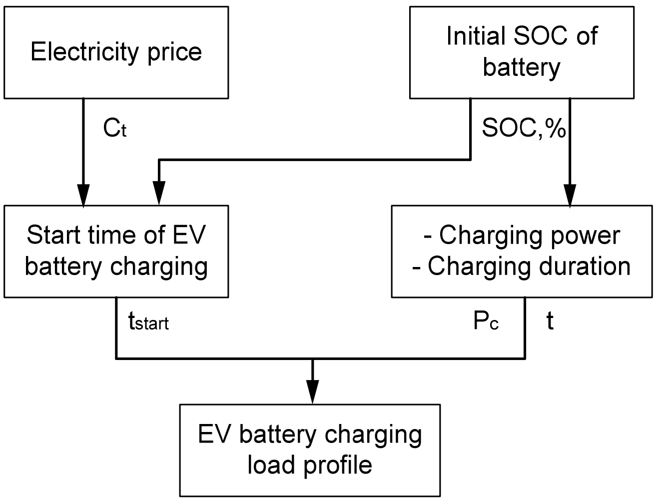

Figure 7. Structure of intelligent EV charging control.

The model of a distribution electrical grid with normal and electric mobile loads is shown in Figure 8. The proposed model consists of the distributed electrical grid powered by an energy source, the transformer, the residential load (offices/small businesses), and the CSs themselves. The situational algorithm is used to simulate the CS operation connected to the electrical grid with a limited power supply. This option of connecting the CS to the electrical grid is the most common case. The system model for studying the effect of EV charging for twenty-four hours is implemented in MATLAB Simulink. The general view of the simulated system is shown in Figure 9.

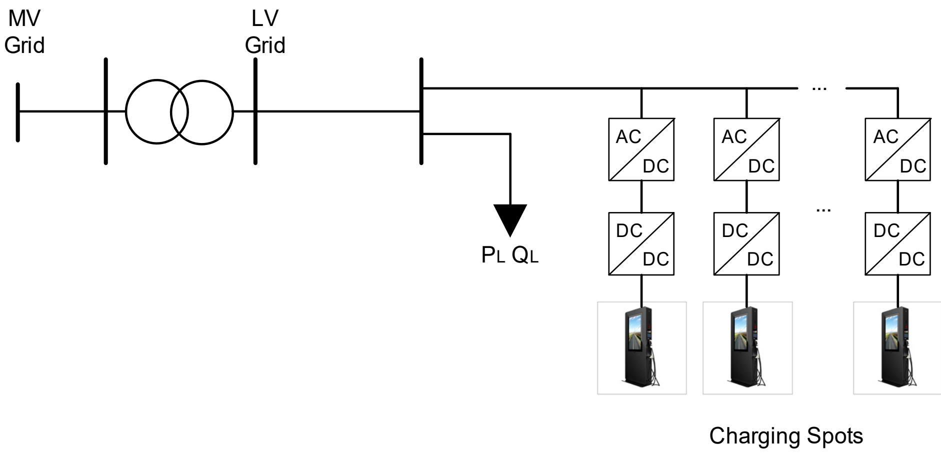

Figure 8. 10.6/0.4 kV distribution microgrid.

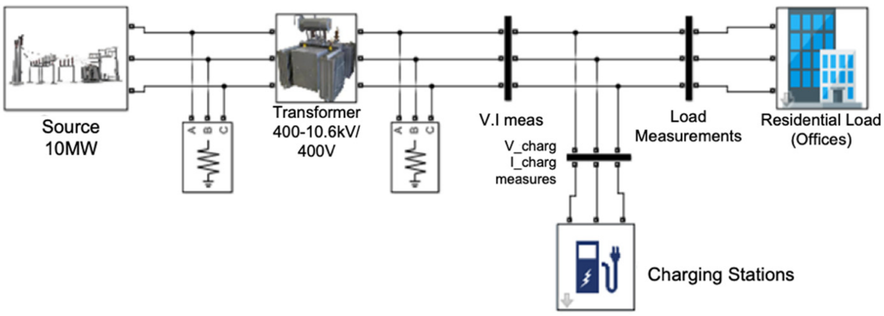

Figure 9. Scheme of the general view of the simulated system.

The consumer (the CLN) has active and reactive energy that can be changed by selecting the power factor PF, which in this case depends on the proportion of the reactive load. The load graph consists of data on the average load of devices and equipment of the administrative building (the CLN) for the period $Tn = 1$ h, $n = 24$ [62]. This data can also be changed. The load schedule in the CLN during the day is shown in Figure 10.

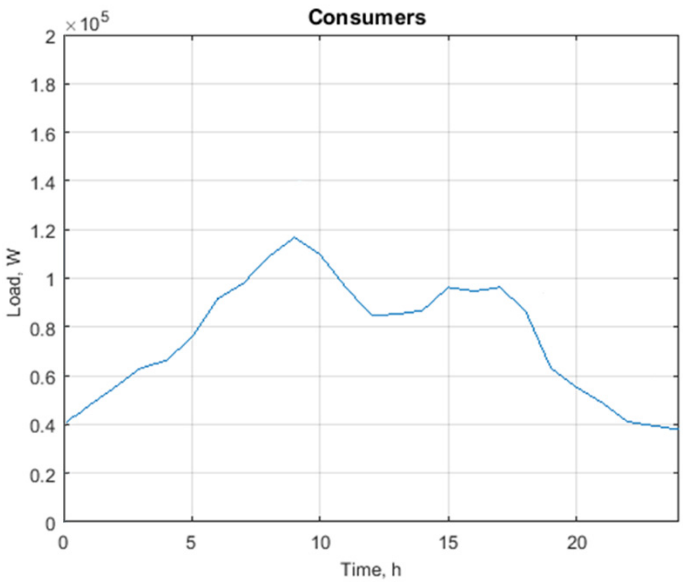

Figure 10. Load schedule in the CLN during the day.

The block diagram of the situational algorithm for controlling the freight EV charging, considering the optimization of the cost of electricity in order to increase the charging efficiency of the independent fleet within the CMFMC, is shown in Figure 11.

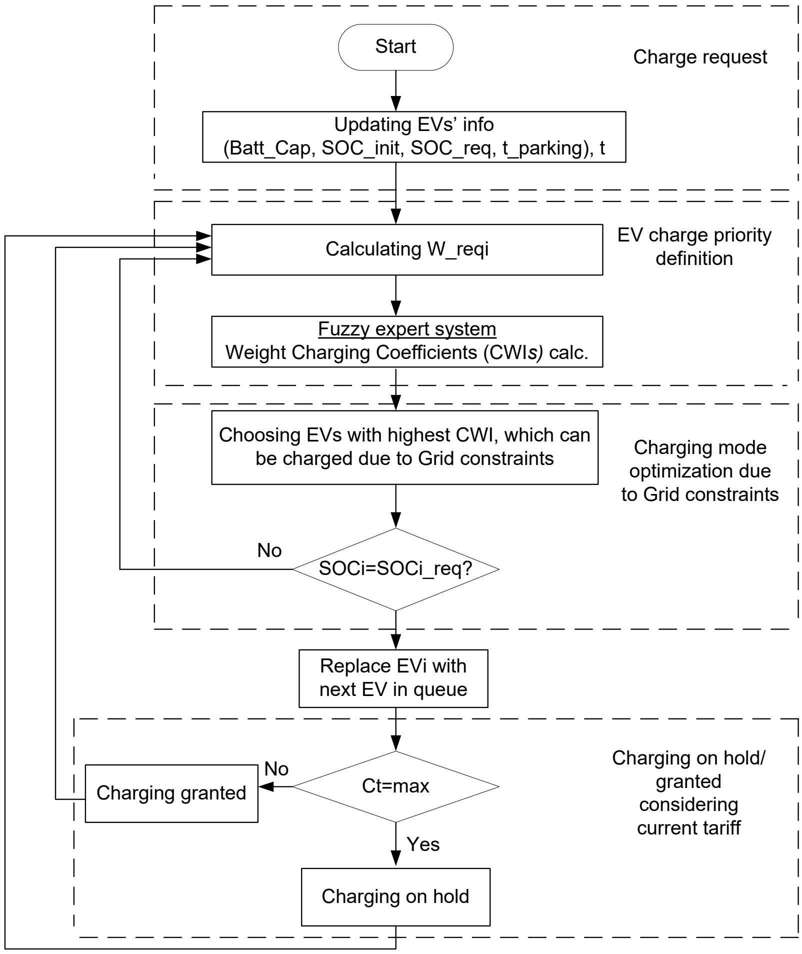

Figure 11. The block diagram of the situational algorithm for controlling the freight EVs charging considering the optimization of the cost of electricity.

The decision to charge or hold an EV is made based on several calculation steps. In the first step, the CWI is calculated for each connected EV to determine its priority by the Fuzzy expert system. The information necessary to calculate the priority of a freight EV, considering the declared duration of its parking (loading-unloading operation) time in the CLN and the required battery charge level, is sent to the Fuzzy expert system from each charging slot. The study used the well-known principles of decision making by the Fuzzy expert system about the charging permission/prohibiting of an EV and calculating its CWI considering membership functions [56]. The second step is the charging mode optimization of EVs connected to the CS, taking into account grid and price limitations, and the final battery charge level. The goal is to select the largest number of freight EVs with high CWI values for charging permission. The last step involves taking into account the electricity tariff at the time of connection of the next priority EV to allow its charging. The decision to charge (1) or not charge (0) an electric vehicle for each charging slot at time t is made based on a situational algorithm.

The energy required for EV charging is defined as the product of the difference between the desired and the initial charge level of the battery with its capacity:

$$W_{req} = \frac{(SOC_{req} - SOC_{start}) \cdot Q_{bat}}{100}, \tag{14}$$

The charging power on the battery side considering expressions (2)–(5) is expressed as a function of SOC, voltage, and charge current:

$$P_{dc} = f_{bat}(SOC, V_{pack}, i), \tag{15}$$

The CS power at the time t of decision making about the charging permission/prohibiting of an EVs:

$$P_{ac(CS)}(t_l) = \frac{P_{dc(CS,t)} \times D_{CS,t}}{\eta_{CS}}, \; CS \in (1, N), \tag{16}$$

The situational algorithm operation involves polling the controller and recalculating the required values for each sampling period (that is, every T = 10 min) throughout the entire twenty-four hour interval for simulating the operation mode of the CS.

4.3. Evaluation of the Effectiveness of the Optimization Model of Intelligent Control of EV Charging and Simulation Results

The effectiveness of EV charging methods and the CS operation mode, considering its load on the electrical grid, was carried out based on the simulation of the control system in the MATLAB Simulink environment. The simulations of the control system were carried out by comparing the proposed situational algorithm of the EV charging based on CWI accounting with the controlled charging algorithm with electrical grid limitations and the uncontrolled charging algorithm. The frequency of receiving information from the CS controller and updating the model, i.e., sampling period, T = 10 min. The time interval for which the task of optimizing the operating mode of the CS is solved is one day, that is, twenty-four hours. Thus, the total number of controlled periods of time during the twenty-four hours: $N_d = 24 \cdot 6 = 144$. The number of periods of the charging profile is calculated for each freight EV, considering the declared parking (loading-unloading operation) time: $N_c = t_{parking}/T$. Uncontrolled charging is limited only by the CS power (24 kW). Transformer and busbar equipment was used with a power limited load up to 120 kW.

The charging strategy based on the controlled charging algorithm for the electricity supplier involves monitoring the transformer load in real-time and limiting the charging process if the electrical grid is overloaded [66]. The power consumption during the twenty-four hour charging scenario for different charging strategies is shown in Figures 12–14.

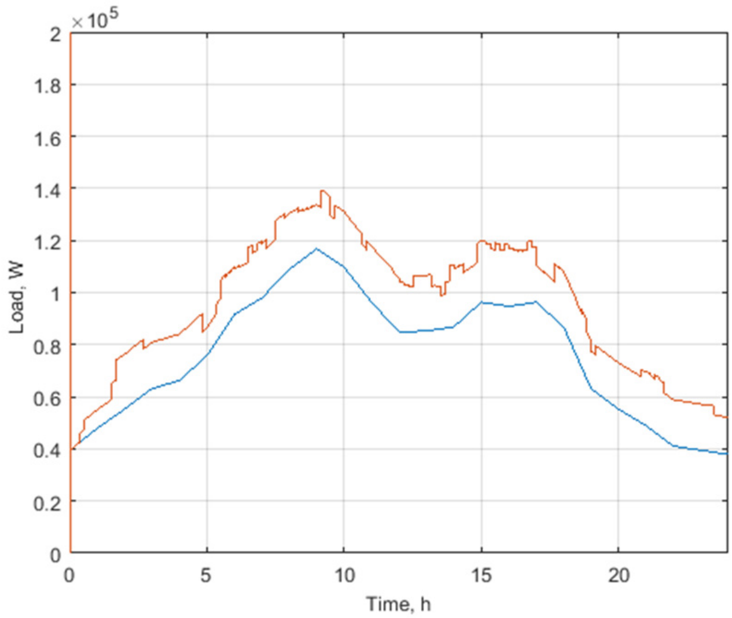

Figure 12. Power consumption over twenty-four hours based on uncontrolled charging. (Brown—general demand; blue—CLN load).

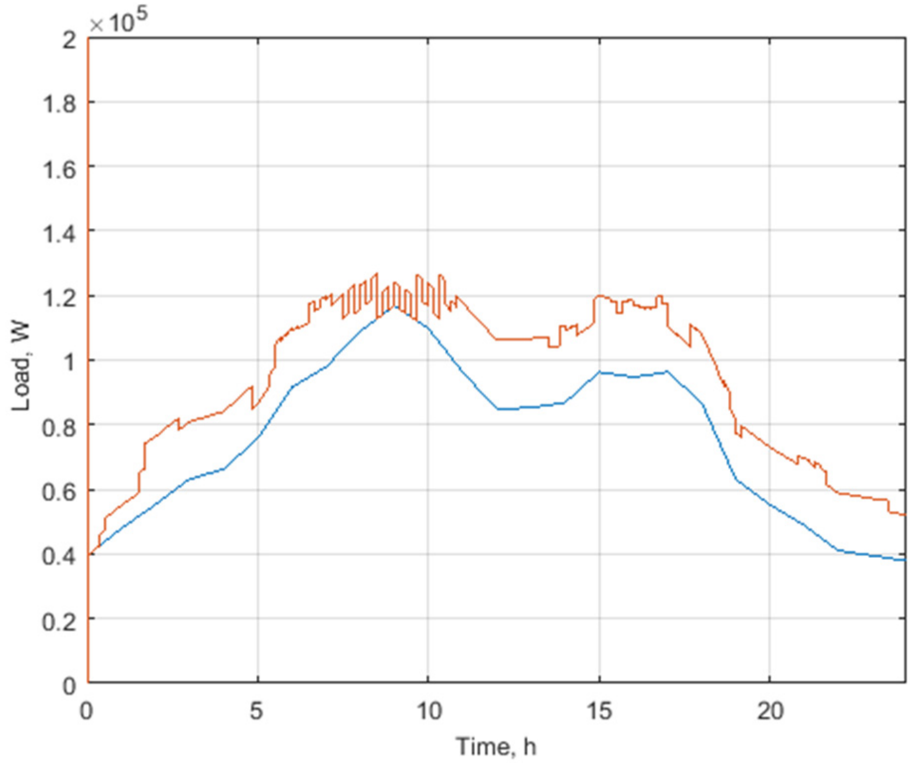

Figure 13. Power consumption over twenty-four hours based on a controlled charge. (Brown—general demand; blue—CLN load).

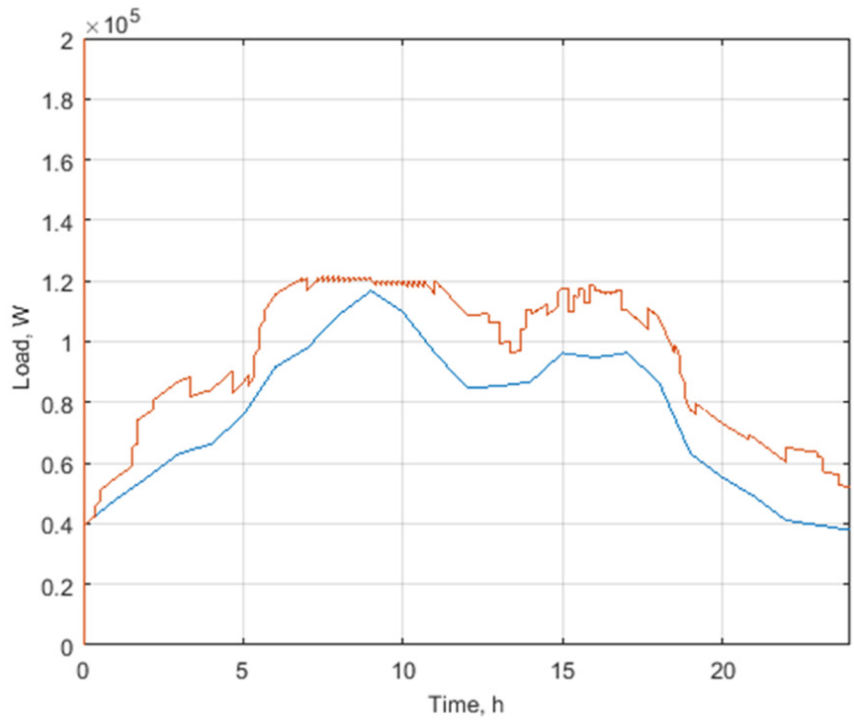

Figure 14. Power consumption over twenty-four hours based on charging according to the proposed situational EV charging algorithm based on CWI accounting. (Brown—general demand; Blue—CLN loading).

Uncontrolled charging leads to an overload of the electrical grid. As for the situational algorithm of EV charging based on CWI accounting and the usually controlled charging algorithm, the energy consumption of freight EVs decreases during peak hours. The situational algorithm of EV charging based on CWI accounting has a smoother curve due to the distribution of the remaining energy, which is not enough to fully charge the battery for the first EV in the queue for charging permission.

The power consumption of freight EVs per the CS for the three strategies are shown in Figure 15. During periods of high electricity prices, the EVs charging according to the proposed situational algorithm consumed 20% less energy, which allowed for a reduction in electricity bills.

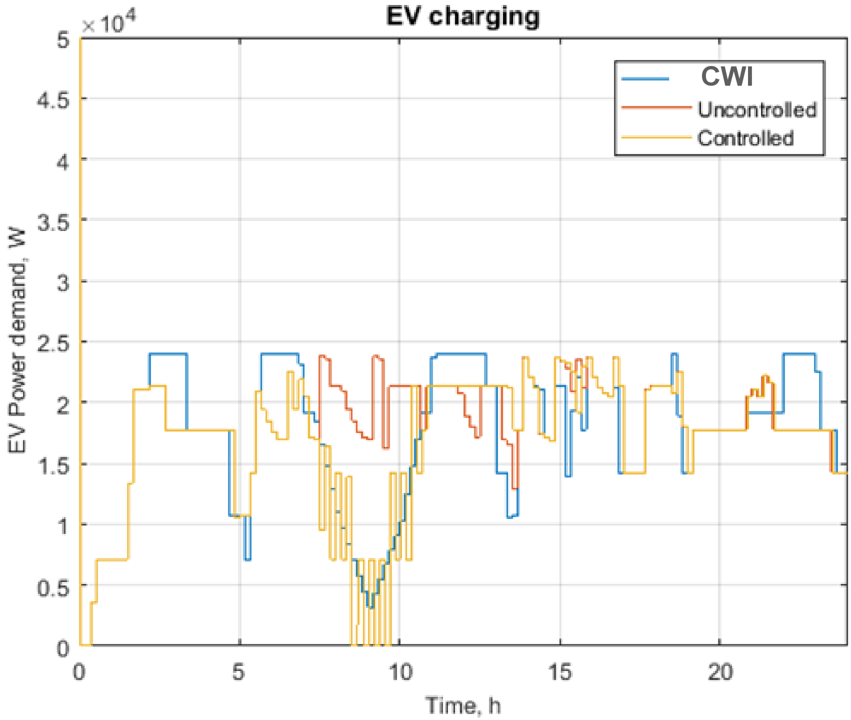

Figure 15. CS charging based on various charging algorithms.

Figures 16 and 17 show the SOC trend for the situation algorithm of EV charging and conventional controlled charging, respectively. In the implementation of the charging strategy according to the conventional controlled charging algorithm undercharging station power limitations, the so-called "first come, first charge" principle is applied [67,68]. This algorithm satisfies electrical grid limitations to prevent its overload. However, its implementation is often inconvenient for EVs that can connect later but require urgent charging and will be parked for a shorter time than previously connected EVs that plan to disconnect later [58]. The most obvious disadvantage of the algorithm in Figure 17 is that the four EVs connected to the 5th and 6th charging points are not charged due to insufficient energy in the electric grid. Critical charging situations, where EVs didn't get enough energy to charge are marked with red circles in Figure 17. The situational algorithm of EV charging proposed in this paper, based on CWI accounting, did not reveal such a drawback—almost all connected freight EVs were charged on SOC demand.

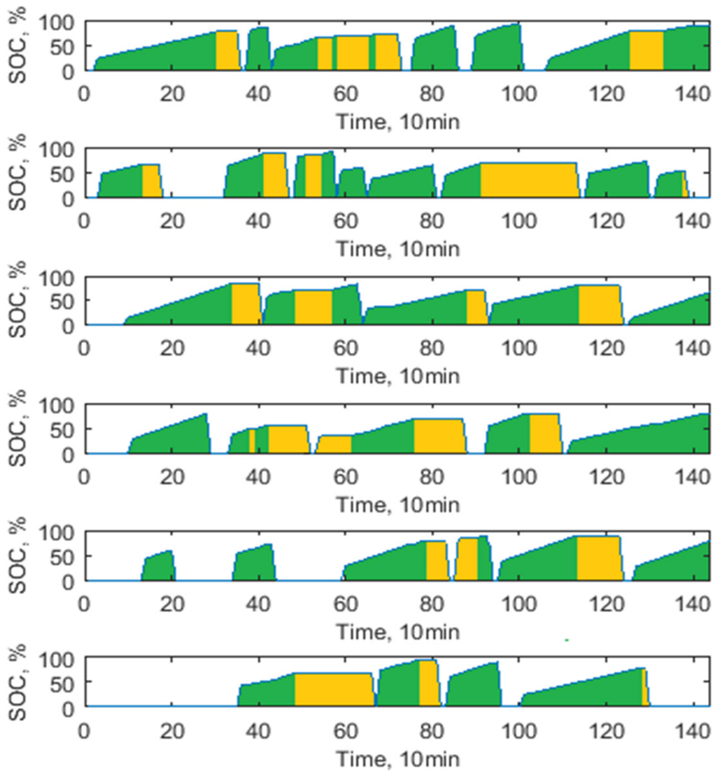

Figure 16. Changes in the SOC of freight EVs at six charging points during charging according to the proposed situational algorithm with CWI (Green—EV is charging; yellow—EV is on hold).

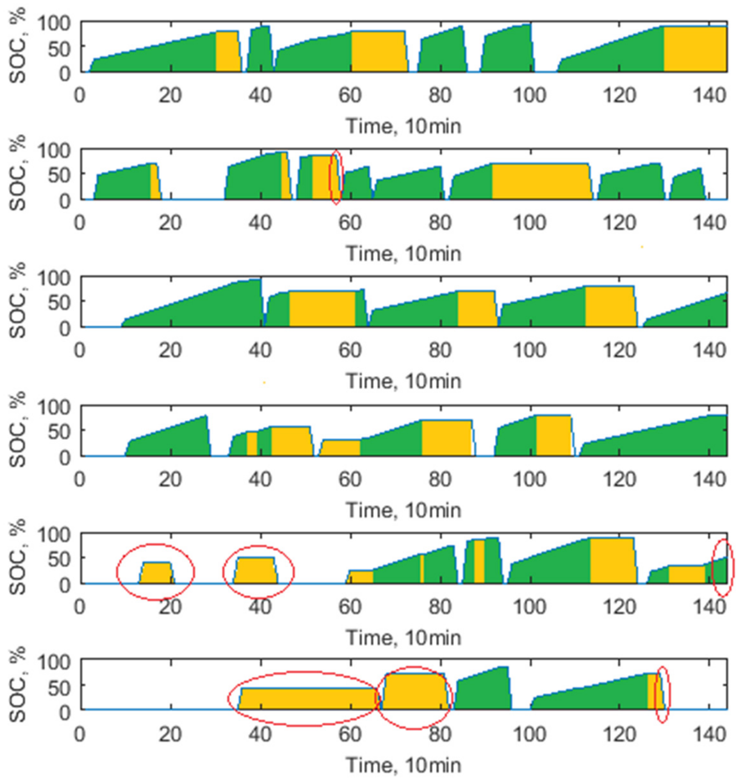

Figure 17. Changes in the SOC of freight EVs at six charging points during controlled charging (Green—EV is charging; yellow—EV is on hold; red circle—critical charging situations).

5. Discussion and Conclusions

The paper is devoted to the real-world problem of the energy-efficient management of an independent fleet of freight EVs within a CMFMC and megapolis. The problem is considered from the standpoint of ensuring sustainable electromobility and efficient operation of the CMFMC, as well as the integration of the independent fleet of freight EVs into the electrical grid and its impact on the electrical load of the power system.

The efficiency of the operation of the independent fleet of freight EVs within the CMFMC is determined by the efficiency of the organization of cargo transportation, the location of CSs in the CLN, and the possibility of combining the loading-unloading operations in the CLN and charging EVs. In addition, the charging strategy of freight EVs and the operating mode of the CSs have a significant impact on the efficient operation of the electrical grid. Therefore, the independent fleet of freight EVs within the CMFMC is considered not only as an end-user of energy but also as an "active" energy consumer and participant in the energy market. This approach requires a joint solution to a set of tasks and considers all aspects of the operation of the independent fleet of freight EVs within the CMFMC and the limitations of the power system.

The complexity of the problem of energy efficiency and the object of study, as well as the need for the comprehensive consideration of information of a different nature from different sources, require the organization and monitoring of the effectiveness of the state of the independent fleet of freight EVs, the organization of the schedule and route of cargo transportation, and electric power consumption, as well as influencing internal and external factors. It should be noted that the monitoring system is considered not just as a data collection system, but as a component of information support for managerial decision-making to implement the principles of smart management. That is, the basis for the functioning of the monitoring system is the integration (accumulation, storage, and processing) of information about all indicators and influencing factors of the functioning of the object of study into a single database, obtaining the data analysis, and planning and controlling the technological, energy, economic indicators.

An object-oriented approach was used to formalize the process of the integrated monitoring of the energy-efficient operation of an independent fleet of freight EVs within a CMFMC. This made it possible to deconstruct the problem under consideration into separate conceptual classes and simplify the description of the components of the problem and the corresponding procedural algorithms. The block structure of the proposed architecture of monitoring information technology is based on the principles of modularity and provides for the possibility of adding new calculation and control algorithms and procedures. This structure meets the requirements for modern information systems and contributes to the development of the monitoring system.

One of the elements of the proposed architecture is the "Operation with the electrical grid" class which combines the tasks of monitoring the CS operation, including planning for the charging of freight EVs, the CS load, and loads on the electrical grid. The purpose of their solution is to improve the efficiency and power consumption of the CS, taking into account the demand for charging the freight EVs and the limitations of the electric power system.

The twenty-four hour simulation of the CS operation for the CLN was performed for the most common case of its connection to the electrical grid with a limited power supply. The planning of the charging of freight EVs under conditions of electric power limitation of the CS is carried out using the situational algorithm for charging EVs which provides for monitoring the charging process. Each EV connected to the CS is assigned a charge weight index which is used to create a short-term charging profile. The CWI depends on the battery charging level, charging speed, required energy, and parking time. The optimization of the electrical load of the CS is carried out from the standpoint of minimizing the electricity costs and ensuring the demand for charging freight EVs without going beyond the limits of restrictions.

A typical commercial distribution system was modeled using the proposed situational algorithm [56], a typical grid-constrained controlled charging algorithm (intelligent charging algorithms), and an uncontrolled charging algorithm. The obtained data are implemented in the model developed by MATLAB Simulink of a typical microgrid with a CS and residential load. The voltages and currents during the charging scenario can be measured at each connection point of the base CS, residential load, general load, or substation. The results show that the electric power consumption with the two controlled charging algorithms is about the same, while the uncontrolled algorithm shows a 16% overload on grid equipment during peak hours. The optimization phase considers the interests and constraints of the electric power supply company and the owner of the CS, such as the CLN. This prevents situations where the freight EV plugs in and fails to charge due to insufficient available energy to service all connected EVs. The algorithm also reduces energy consumption during times of high electricity prices. The proposed algorithm for SEMS of EV charging, considering the electricity tariff, reduces energy consumption during high electricity prices, thereby reducing the cost of the enterprise for charging freight EVs. The considered example of using the situational algorithm for twenty-four hours of modeling of the CS operation allows its advantages to be shown in a simple form.

The practical value of the proposed approach to solving the problems of the CS operation monitoring is to develop a simulation layout and physical modeling of the "electrical grid-charger-EV" circuit in order to optimize the charging mode of the independent fleet of freight EVs within the CMFMC. The proposed MATLAB Simulink model can be scaled to the required size of the power grid under study (with centralized or decentralized control of distribution power grids). Limitations of this research are related to the possibilities of modeling the charging control of freight EVs in order to optimize power consumption and minimize electricity costs within the CMFMC.

In future studies, by using the MATLAB Simulink model proposed in this paper, it will be possible to conduct various simulations with the V2G system to improve the energy efficiency of the independent fleet of freight EVs within the CMFMC. At the same time, the issue of the level of battery degradation and the degree of its influence on the amount of charging/discharging energy needs to be addressed. It is assumed that the development of the energy efficiency monitoring system for the independent fleet of freight EVs within the CMFMC will allow for systematically obtaining information on the change in the coefficient that takes into account the level of degradation of the electric vehicle battery. The development of a methodology for its calculation and accounting in the proposed situational algorithm for controlling the operating mode of the CS, and a case study of algorithms and procedures for implementing other classes of the proposed information technology architecture, are the subject of future research.

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Nomenclature

CWI	Charge weight index
P_{dc}	Charge power on the battery side (kW)
P_{ac}	Charge power on the electrical grid side (kW)
SOC	Battery charge level (%)
SOC_{reg}	Required value of the battery charge level of the EV (%)
SOC_{strart}	Initial value of the battery charge level of the EV (%)
V_{OCeq}	Voltage of the controlled equivalent voltage source (V)
V_c	Voltage of the electrical grid (V)
V_{pack}	Voltage on the battery side (at the battery terminals) during charging (V)
i_c	Current of the electrical grid during charging (A)
i	Current on the battery side during charging (A)
Q_{bat}	Battery capacity (Ah)
W_{req}	Energy needed to charge the EV (kWh)
$t_{parking}$	Charging time (parking time) of the EV (h)
μ	Membership function
η	Energy conversion efficiency of the charger
R_{eq}	Equivalent resistance (Ohm)
T	Sampling time step (min)
j	Profile step (period) number during charging
$dQ(j)$	Battery capacity change in step j (Ah)
N_c	Number of steps (periods) of the charging profile
N_d	Number of steps (periods) of discretization during twenty-four hours
N	Number of CS slots (pcs.)
P_s	Power of the CS on the electrical grid side (kW)
C	Electricity tariff (p.u./kWh)
$P_s{}^{max}$	Power limits for a moment in time t (kW)
P_L	Household power load (kW)
k	Number of the charging start period
l	Number of the current time period
$f(t_k)$	Probability of starting the charging process on the k-th period
$F(P_j,t_1)$	Probability of charging power consumption in the l-th period at the beginning of charging in the k-th period
$h(SOC_j)$	Probability of the battery SOC the j-th period, considering the charging start period
$x(t)$	Percentage of freight EVs that received the stated charging level (%)
$D_{CS,t}$	Decision to charge (1) or not (0) for the charging slot for time t
CS	Number of the charging slot

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