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Electric vehicle charging management system in the industrial zone

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Abstract: The transportation sector is undergoing a profound transformation, shifting from fossil fuel reliance to electric and hybrid semi-electric alternatives. In response, European countries are implementing novel concepts like electrified highways for trucks and buses, bridging the gap between traditional and electric mobility. This paper centers on the management of electric vehicle (EV) charging infrastructure within industrial zones, crucial nodes for charging networks due to their concentrated economic activity and vehicular movement. The study delves into optimal strategies for deploying charging stations in these zones, considering factors such as station placement, capacity planning, and integration with smart grids to ensure efficient and accessible EV charging. Moreover, the research extends its focus to the integration of vehicle-to-grid (V2G) and grid-to-vehicle (G2V) technologies, illustrating their potential within industrial zones. In our research, we have developed algorithms tailored for the infrastructure of industrial zones, focusing on the integration of storage systems and the charging and discharging dynamics of electric vehicles (EVs). Our case study, supported by numerical simulations, illustrates the outcomes of a 24-hour timeframe, where 126 vehicles were charged, and 134 were discharged. The results provide a comprehensive view of how the grid-maintained balance throughout these operations, ensuring that industrial facilities received the required power to fulfill their operational demands.

Key words: energy storage system, EVs charging infrastructure, G2V, hybrid electric vehicles, PEVs, V2G

1. Introduction

EVs have a history spanning several decades, yet they only began gaining significant market traction after Elon Musk introduced the first Tesla in 2003 [1]. During the period before this transformative shift, EVs faced obstacles that impeded their market penetration. Technological limitations in battery development hindered their practicality, while the lack of charging infrastructure, coupled with manufacturing challenges, posed hurdles to their widespread adoption. Awareness regarding global warming and environmental issues was limited, and the powerful influence of the oil industry further shaped the automotive landscape. However, our perspective has since evolved, and the focus has shifted towards sustainability and a greener environment.

In the context of plug-in electric vehicles (PEVs), the discussion inevitably centers on batteries, charging infrastructure, electricity availability, and management. A sudden and complete transition to 100% electric mobility is not feasible due to our current grid's limitations. Therefore, careful consideration is required regarding where, how, and to what extent we need charging infrastructure, while also assessing its impact on the existing power grid.

The primary charging infrastructure needs to align with the current limitations of EV battery capacity and range. Home-based charging stations hold significant potential, catering to approximately 50–80% of all charging events. Following this, workplace charging assumes a critical role, accounting for 15–25% of charging occurrences. Public slow charging stations and long-distance travel corridor charging constitute the remaining charging locations, each contributing less than 10% of the total charging demand [2].

According to a research study, the current high-voltage (HV) power system in the USA is believed to be capable of fulfilling 73% of the EV demand if conventional internal combustion engine vehicles were to be replaced. Achieving this would require prudent planning and anticipatory growth in the high-voltage infrastructure [3]. However, investigations have revealed that the distribution systems are susceptible to being significantly impacted.

The rapid expansion of EVs is exerting significant pressure on the utility sector. The mounting demand for electricity to power these EVs presents a formidable challenge for utilities, straining their capacity to meet this surge. The consequence of this exponential increase in EVs plugging into the electricity grid raises concerns about the adverse effects it might have on grid management. To effectively address this, an ongoing commitment to monitoring, research, and evaluation becomes imperative in comprehending the intricate repercussions of EV integration on both the power system and distribution network [4, 5, 8–10]. The charging of EVs gives rise to a notable concern regarding harmonic pollution. EVs, being nonlinear loads, play a role in this issue. Disorderly and rapid charging processes have the potential to exacerbate the occurrence of harmonic pollution. The presence of harmonics results in the distortion of power signals and a decrease in the power factor, as detailed in reference [11].

Amid this backdrop, various studies have emerged, proposing techniques to manage EV charging and alleviate the potential strain on the electricity grid. These techniques encompass centralized charging control, which involves coordinated management of charging schedules, decentralized charging control, empowering individual EVs to adapt their charging patterns, and autonomous charging control mechanisms. Implementing these strategies offers a promising approach to mitigating the substantial impacts that EVs might otherwise exert on the electricity grid [6]. As the EV landscape evolves, the integration of advanced charging techniques serves as a pivotal pathway towards a harmonious coexistence between EV adoption and grid stability.

Another research that focuses on examining online monitoring, detecting faults, diagnosing issues, and assessing the condition of charging facilities and their related equipment. This comprehensive review aims to offer valuable insights to fellow researchers and scientists, aiding them in gaining a wider perspective to discover more effective tools and techniques in this domain [12].

A distributed vehicle charging management algorithm grounded in local voltage measurements was showcased in "A distributed electric vehicle charging management algorithm using only local measurements" [13]. The perspective adopted was that of the distribution grid, and the strategy involved making decisions at the household level. The primary objective is to optimize grid utilization to the fullest extent while maintaining equitable charging opportunities for all users. Likewise, another research has proposed the concept of a distribution charging infrastructure within the Czech region. The objective was to evaluate diverse approaches for electric vehicle charging and to establish a comprehensive framework for charging station concepts [14, 16].

In a similar vein, two intelligent methodologies have been devised, each encompassing distinct objective functions – one focused on minimizing total daily costs and the other on reducing the peak-to-average ratio (PAR). These strategies have been constructed to delve into the economic and technical ramifications of PEV charging [7].

Another technique explored for electric vehicle charging scheduling involves the application of artificial neural networks (ANNs). In addition to presenting the ANN method, researchers delve into the significance of advanced metering infrastructure in the context of scheduling. The primary emphasis lies on establishing machine-to-machine communication as a pivotal link for aligning utility power forecasts with the charging demands of EVs [15].

In this paper, our approach is to design electric vehicle charging management systems in the industrial zone. We have considered different industries and their overall load with renewable energy to some extent and zonal-level energy storage systems. The algorithm for electricity flow at the zone level with an energy storage system is demonstrated to understand the overall charging pattern of EVs. We have considered both V2G and G2V.

2. Smart network in industrial zone

To begin with, let's delve into the configuration of the smart network, as portrayed in Fig. 1. This intricate system consists of diverse elements, including sectors of industry, grid storage setups, infrastructure for electric vehicles, and pivotal grid components such as the central grid connection, which comes furnished with monitoring and management controllers.

The central grid connection, along with its controller, can receive power from three different sources: direct grid supply, distribution storage supply and V2G energy supply.

The grid is set up in a circular way, like a ring, to help use electricity efficiently by letting people share power directly. This setup is also useful because if there's a problem in one area, electricity can still flow through other paths. Each part of the system, like different industries, has a smart panel that can connect and disconnect based on how much electricity is available.

A really important part is the controller that manages everything. It can send extra energy back into the main grid. Another important thing is power electronics, which helps change energy at different levels. It works together with the energy storage system (ESS) for each zone. There are smart switches that work automatically to protect transformers and measure energy flow.

The system also has lots of sensors. One sensor can figure out different energy sources, while another can stop electricity if there's a problem. There are sensors to control voltage, send alerts to the main grid, and even fix missing sensors.

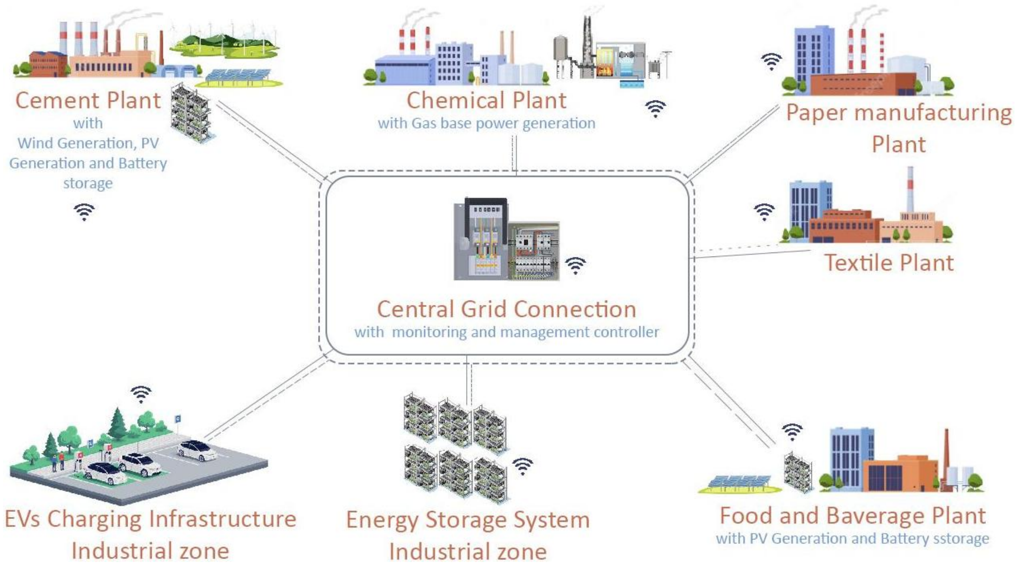

Fig. 1. Smart network layout

The focus is on making EV charging better. This means getting industries and utilities to work together to create energy storage and improve EV charging spots. The government can also help by giving money to support these efforts.

The main controller can use three types of energy sources. These sensors know when each source is available and connect them as needed. Sensors are working controller guidance which is operated by algorithms. In the next section we will see the equation used for the electrical energy flow in the industrial zone and for the industrial energy storage system [17].

3. Mathematical equations utilized to create models for the grid

The provided mathematical equations are utilized to create models for the grid, and these equations are directly employed in algorithms. All the equations given in this section is dynamic in nature.

Illustrated by Eq. (1), load balancing within the industrial zone is evident. This demonstration showcases the equilibrium achieved through a combination of utility power supply, discharge from industrial storage, and vehicle to grid (V2G) electricity utilization.

$$U_t^z + \left(\frac{p_t^{dz}}{\eta_d^z}\right) + \sum_{i=1}^{45} p_{it}^{\mathrm{V2G}ev} \geq \left(\sum_{l=1}^{5} D_{lt}^z + \sum_{j=1}^{45} p_{jt}^{\mathrm{G2V}ev} + \left(p_t^{cz} * \eta_c^z\right)\right) * \Delta t * k, \tag{1}$$

where: U_t^z is the utility power at time t at the industrial zone (kW), p_t^{dz} is the battery discharging power at time t at the industrial zone (kW), η_d^z is the battery discharging efficiency at time t at the industrial zone (%), $p_{it}^{\mathrm{V2G}ev}$ is the electrical vehicle V2G power at time t, i is the number of electric vehicles chargers, D_{it}^z is load at time t at industrial zone (kW), l is the number of industries, $p_{jt}^{\mathrm{G2V}ev}$ is the electrical vehicle G2V power at time t, j represents the number of electric vehicle chargers, η_c^z is the battery charging efficiency at the industrial zone (%), p_t^{cz} is the battery charging power at time t at the cement industry (kW), Δt is the time constant measured in minutes (it is a difference in time between the consecutive measurement, it is the interval over which changes in the state of charger and power are considered), k is the variable constant (k is used as balancing the equation, scales the right side of the inequality. It is a multiplier that influences the balance or significance of the right side concerning the left side, due to which no unit is defined).

In the context of the V2G and G2V interaction, the equation encompasses a range of chargers from $i = 1$ to 45, representing the comprehensive consideration of 45 charging and discharging units.

Equation (2) signifies the state of charge within the storage system situated in the industrial zone.

$$\mathrm{SOC}_t^z = \mathrm{SOC}_{(t-1)}^z + \left(p_t^{cz} * \eta_c^z + \frac{p_t^{dz}}{\eta_d^z}\right) * \Delta t, \tag{2}$$

where: SOC_t^z is the state of charge of the battery at time t at the industrial zone, SOC_{t-1}^z is the state of charge of the battery at time $t-1$ at the industrial zone.

Equation (3) signifies the state of the industrial storage system charging.

$$p_t^{cz} * \eta_c^z = U_t^z + \sum_{j=1}^{45} p_{jt}^{\mathrm{V2G}ev} - \left(\left(\sum_{i=1}^{5} D_{it}^z + \sum_{j=1}^{45} p_{jt}^{ev}\right) * \Delta t * k\right), \tag{3}$$

Conditions: charging with $U_t^z \rightarrow t = 11{:}00$ PM $\rightarrow$ 4:00 AM,

$$\mathrm{SOC}_{\min}^z \leq \mathrm{SOC}_t^z \leq \mathrm{SOC}_{\max}^z, \quad p_{\min}^{cz} \leq p_t^{cz} \leq p_{\max}^{cz},$$

where: $\mathrm{SOC}_{\min}^z$ is the minimum limit of the state of charge of the battery at the industrial zone, $\mathrm{SOC}_{\max}^z$ is the maximum limit of the state of charge of the battery at the industrial zone, $p_{\min}^{cz}$ is the minimum limit of the charging power at the industrial zone (kW), $p_{\max}^{cz}$ is the maximum limit of the charging power at the industrial zone (kW).

Equation (4) signifies the state of industrial storage system discharging.

$$\frac{p_t^{dz}}{\eta_d^z} = \mathrm{SOC}_{(t-1)}^z + U_t^z + \sum_{j=1}^{45} p_{jt}^{\mathrm{V2G}ev} - \left(\left(\sum_{i=1}^{5} D_{it}^z + \sum_{j=1}^{45} p_{jt}^{ev}\right) * \Delta t * k\right), \tag{4}$$

Conditions: discharging at t =11:00 AM to 6:00 PM,

$$p_{\min}^{dz} \le p_t^{dz} \le p_{\max}^{dz},$$

where: $p_{\min}^{cz}$ is the minimum limit of the charging power at the industrial zone (kW), $p_{\max}^{cz}$ is the maximum limit of the charging power at the industrial zone (kW).

Having gained an understanding of the equation, the subsequent section aims to elucidate the algorithm's mechanics. This discussion will shed light on the intricate manner in which these equations actively participate in the management of grid power flow. Moreover, this exploration will unveil the pivotal role that EVs play in influencing the dynamics of the grid [17].

4. Algorithm for energy flows and energy storage in an industrial zone

Within this section, the focus shifts toward illustrating the algorithm governing energy flow within the industrial zone, as well as delving into the charging algorithm for energy storage at the same location. Through detailed exposition, the mechanisms underlying these processes will be revealed, offering a comprehensive understanding of how energy dynamics are managed within industrial settings.

4.1. Energy flow algorithm at industrial zone

Figure 2 presents an illustrative depiction of the energy flow algorithm put into practice within the industrial zone. This algorithm operates in a time-dependent manner, considering the current time as a fundamental factor in its decision-making process.

Figure 2 contains abbreviations which are explained as follows: U. Power – utility power, Z. Bat. Dis. – zonal battery discharge, EVs Dis. – EVs battery discharge, I.L – industrial load, EVs Char. – EVs battery charging, Z. Bat. Char. – zonal battery charging, ZA – go to block if U. power is not greater than or equal to I.L. + EV charging, ZB – go to block if U. power is not available, Z-BCA-U – zonal battery charging algorithm from U. power, Z-BCA-EVU – zonal battery charging algorithm from U. power and EV (V2G) discharge, Z-BCA-EVU – zonal battery charging algorithm from EV (V2G) discharge, Supply Power – supplying power to industrial load.

The algorithm is executed at the entry-level controller situated at the zonal step-down transformer. Power is sourced from various channels, including utility power, EV V2G, the zonal-level energy storage system (zonal battery), and combinations thereof. The supplied power is directed towards industrial loads, EV G2V charging, and the zonal-level energy storage. Different conditions are defined for power supply, depending on the availability of power from these various sources. An alert system is in place to notify industries in case utility power is unavailable during peak hours. A 15-minute cycle and continuous feedback form are implemented as part of the necessary arrangements.

The assessment of utility power availability takes precedence as the primary focus. In the absence of utility supply, the algorithm initiates a sequence of evaluations. It first checks whether the industrial storage unit has reached the minimum required state of charge. Simultaneously, an alert is sent to all industries, notifying them of the absence of power from the utility. If the storage unit has sufficient capacity, power provision proceeds accordingly. Otherwise, the algorithm

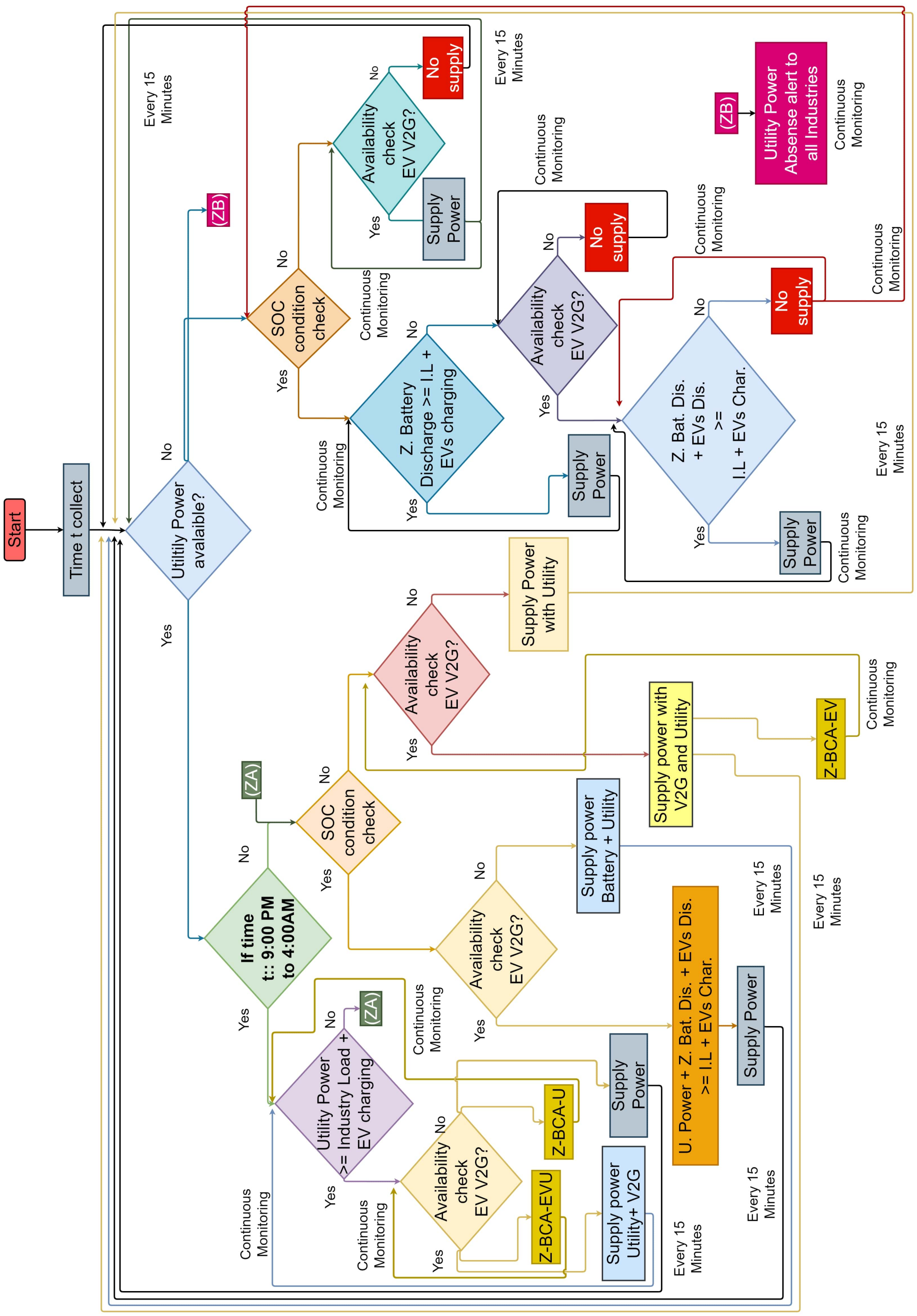

Fig. 2. Energy flow algorithm at industrial zone

explores the feasibility of using electric vehicles (EVs) to supply power to the industrial load. In the absence of available EVs, power will be paused until utility power is restored. On the other hand, if the storage system has power but not enough to meet the industrial load, power will be supplied in combination with EVs V2G. Multiple conditions are verified to supply power to industries and facilitate EV charging.

Upon utility power restoration, the algorithm takes into account the timing, assessing whether it falls within the predefined window of 9:00 PM to 4:00 AM designated for zone battery charging. In cases where the time lies outside this interval, the algorithm appraises the battery's charge state. Subsequently, it evaluates the V2G circumstances, allocating power if it meets the required threshold. When power sufficiency is not achieved, a fusion of utility power and battery supply is orchestrated to cater to the industrial load and charge the zonal battery with limited charging capacity. Instances where the battery's charge falls below the designated minimum mark prompt a review of EV availability. Prioritizing V2G conditions, the algorithm allocates power, subsequently fulfilling the remaining load through utility supply. In situations where charging the zonal battery and power from EVs are insufficient to provide the required power, a combination of utility power, zonal battery power, and vehicle-to-grid (V2G) operations is employed to support the load.

In the third scenario, occurring within the stipulated time range, load fulfillment transpires via utility power. It will supply power to industries and EVs G2V charging if any vehicles are connected. Also, it will assess the condition further if EVs V2G available power will be supplied in combination with industries, EVs charging and charging the zonal battery. In cases where EV power is unavailable and the load hasn't reached its peak limit, the battery replenishes using utility power.

4.2. Energy storage charging algorithm at industrial zone

The operational framework of the industrial energy storage algorithm, as depicted in Fig. 3, collaborates closely with the zone energy flow algorithm to ascertain the most optimal means and timing for battery charging. This pivotal phase encompasses three potential avenues for battery charging, all intricately interlinked with the predefined parameters scrutinized within the zone energy flow algorithm. Central to the core objective of this algorithm is the evaluation of the battery's charge state, probing whether it has reached full capacity. Employing a perpetual feedback loop, it diligently monitors the conditions aligned with the zone energy flow algorithm. The overarching goal is to facilitate a smooth and uninterrupted battery charging process, attuned to the evolving conditions of the system.

Within the discussed algorithms, the incorporation of EV capabilities, particularly vehicle-to-grid (V2G) interactions, is closely intertwined with the presence of an industrial storage system.

In the zone energy flow algorithm, the incorporation of V2G is strategically aligned with the industrial storage setup. As depicted in Fig. 3, the zonal storage system can receive a charge through the Z-BCA-EVU loop when both utility power and EVs V2G have surplus power available after meeting the requirements of industrial load and EVs grid-to-vehicle (G2V). Simultaneously, a parallel condition exists: if EVs are unavailable and power is still accessible from the utility after

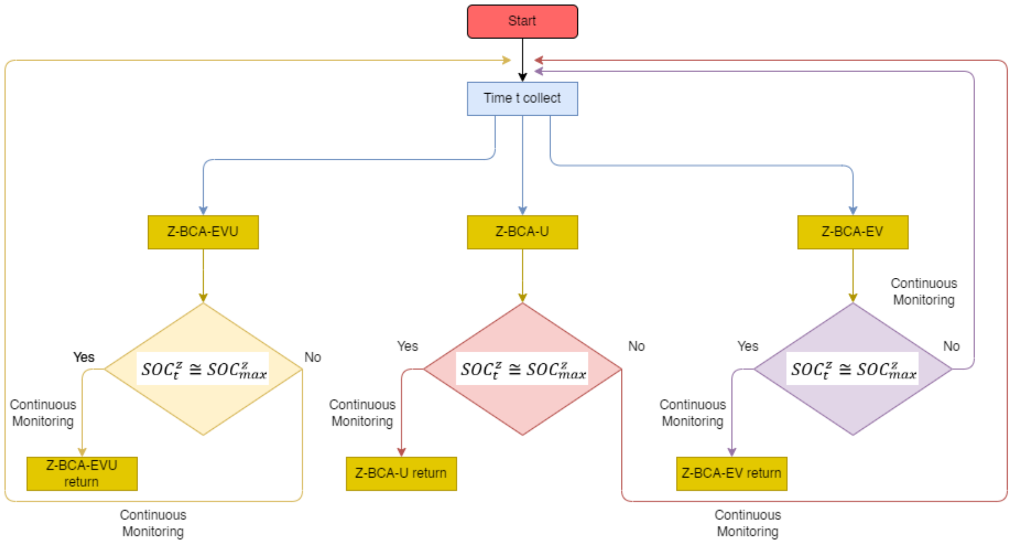

Fig. 3. Battery charging algorithm at industrial zone

fulfilling the load, then the charge will be provided through the Z-BCA-U loop. Both of these conditions occur when industries are not operational within the predefined time zone.

The last condition arises when industries are operational, and the zonal battery receives a charge from EVs. This occurs when both industrial load and G2V requirements are met by utility power. The maximum charge condition is set at 100% of the battery capacity, and the minimum charge condition to supply power is above 10% of the battery capacity.

In the context of the industrial energy storage algorithm, the industrial storage system amplifies the potential of V2G. This integration guarantees that battery charging aligns with grid demand, encompassing both EVs' charging and discharging necessities. This bidirectional power exchange illustrates the symbiotic relationship between grid dynamics and EVs, contributing to energy optimization and grid stability [17].

5. Case study

Within this section, we elucidate the case study, present relevant graphs. Additionally, we outline the quantity of electric vehicle charging infrastructure, distinguishing them by varying charging speeds and capacities.

5.1. Cars and their charging and discharging pattern

We have taken into consideration seven distinct car types, categorized based on their maximum charge capacity.

Table 1 contains information regarding seven distinct car categories, encompassing their charging and discharging cycles. Within this table, we have computed the time disparity between charging and discharging cars, considering the overall efficiency of the car's battery and charger.

Table 1. Car type, charging and discharging cycle

Car type	Max. battery size (kW)	Max. power required to charge from zero (kW)	Max discharge possible from full battery (kW)	Amount of discharge can provide (kW)	Time to charge a battery (minutes)	Time to charge a battery (hour)	Time to discharge a battery (minutes)	Time to discharge a battery (hours)
1	118.00	138.82	94.40	80.24	55.53	0.93	37.76	0.63
2	74.00	87.06	59.20	50.32	34.82	0.58	23.68	0.39
3	75.00	88.24	60.00	51.00	35.29	0.59	24.00	0.40
4	65.00	76.47	52.00	44.20	30.59	0.51	20.80	0.35
5	64.00	67.37	51.20	46.08	87.87	1.46	66.78	1.11
6	40.00	43.48	32.00	27.84	176.26	2.94	129.73	2.16
7	66.00	71.74	52.80	45.94	290.83	4.85	214.05	3.57

The calculations employed for generating Table 1, as well as the capacities of the chargers, are outlined below.

Three different chargers are considered which are as follows:

1. Super-fast Charger: 150 kW (5 chargers)
2. Fast Charger: 46 kW (15 chargers)
3. Medium Speed Charger: 14.8 kW (25 chargers)

Car type: 1, 2, 3, 4: 118 kW, 74 kW, 75 kW, 65 kW
Charged and discharged: Super-fast Charger
G2V, charging efficiency (combined): 85%
V2G, discharge efficiency (car): 80%
V2G, discharge efficiency (charger): 85%
Car type: 5: 64 kW
Charged and discharged: Fast Charger
G2V, charging efficiency (combined): 95%
V2G, discharge efficiency (car): 80%
V2G, discharge efficiency (charger): 90%
Car type: 6, 7: 40 kW, 66 kW
Charged and discharged: Medium Speed Charger
G2V, charging efficiency (combined): 92%
V2G, discharge efficiency (car): 80%
V2G, discharge efficiency (charger): 87%

5.2. Case: grid with EV Infrastructure and industrial zone storage – grid management scenario

The focus of this scenario lies in the presence of EV infrastructure and on-site energy storage within the industrial zone, thus enabling a comprehensive framework for grid management. The objective revolves around formulating a robust strategy to govern the grid, encompassing both the power needs of the EV infrastructure and the industrial zone. The integration of these facets stands to optimize the utilization of renewable energy, bolster grid stability, and enhance overall energy efficiency.

The algorithm assumes the responsibility of evaluating power requisites originating from both the EV infrastructure and the industrial zone. This evaluation takes into account variables such as charging patterns, fluctuations in load, and levels of energy stored. By analyzing these dynamic factors, the algorithm discerns the most favorable allocation of power. This allocation spans across renewable sources, on-site storage, and the utility grid.

The algorithm's effectiveness is magnified by its simulation capabilities, facilitating adaptability in alignment with grid conditions. This agility not only sustains grid stability but also curtails dependency on non-renewable sources. Complementary considerations encompass the assessment of energy storage capacity, availability of renewable energy resources, and contractual agreements with utility providers.

The realization of this grid management paradigm equips industries to optimize the utilization of renewable energy, decrease reliance on the grid, and streamline energy consumption. This holistic approach advocates sustainability, thereby fostering an ecologically balanced and energy-efficient ecosystem.

Illustrated in Fig. 4 is the load pattern of five distinct industries, spotlighting the dispersion of power consumption across them.

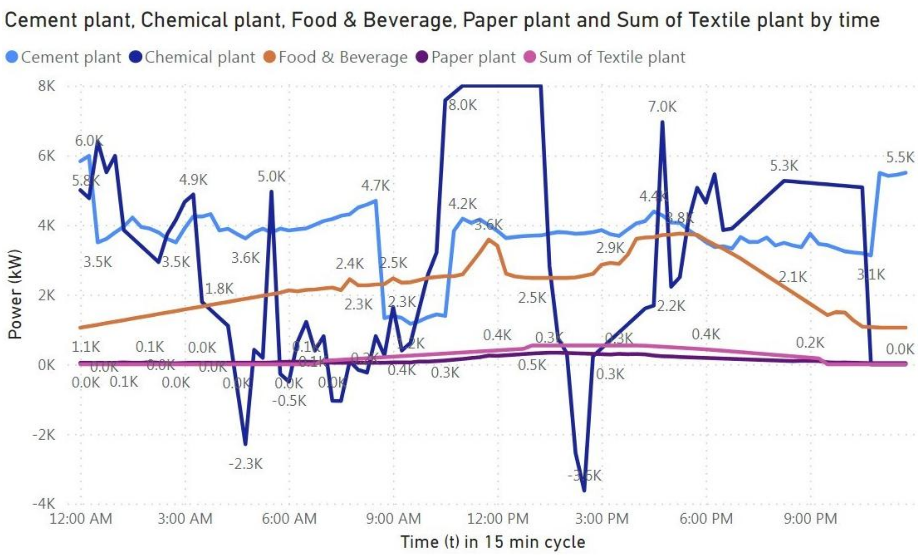

Fig. 4. Industrial load

The chemical and cement sectors emerge as the most power-intensive, with the chemical industry peaking at 8 000 kW or 8 MW during periods of heightened demand. It's noteworthy that an operational glitch transpired within the chemical industry, causing a dip in power supply. This deficiency was subsequently offset by gas power generation within the same industry. The surplus power generated by the gas plant was then channeled into the local industrial grid, thereby benefiting neighboring industries.

Furthermore, the paper and textile industries exhibit the least power-intensive profiles within this grouping, signaling their comparably modest energy requisites. Notably, during phases of elevated demand, the cement industry showcases a notable reduction in power consumption. This phenomenon alludes to potential load-shifting practices or adaptations in production processes. Lastly, the food and beverage sector maintain a consistent power consumption level in relation to the other industries, mirroring its moderate energy demands.

A thorough examination of these load patterns provides a holistic insight into the power consumption dynamics unique to each industry. This data holds immense significance in devising effective energy management tactics that are finely tuned to the distinct attributes and requirements of each industry.

Furthermore, this analysis also provides insights into the number of vehicles that undergo charging and discharging processes during this timeframe, showcasing how this synchronized energy ecosystem benefits both industries and electric vehicles alike.

Figure 5 furnishes an insight into the accessible utility power throughout the day with 15 minutes cycle analysis.

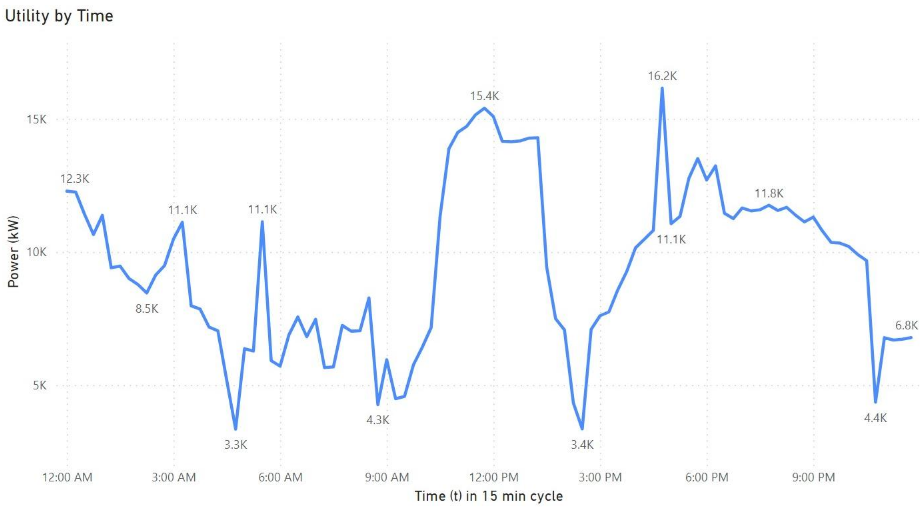

Fig. 5. Utility power at industrial zone

The dynamic nature of power supply is taken into consideration to comprehend the intricacies of the given algorithms and support various loads. Even during peak operational hours of industries, a decrease in utility power has been observed to evaluate the capacity of zonal energy storage systems and the supply from EVs through V2G. The highest power supplied by the utility at any given time is 16 200 kW, and the highest combined industrial load at any given time is 16 800 kW. This underscores the absolute necessity of an energy storage system to support industrial operations and meet the anticipated future demand from EVs.

In Fig. 6, the state of charge of the zonal storage system is depicted, providing a clear insight into how energy is utilized during the peak hours of industrial operations.

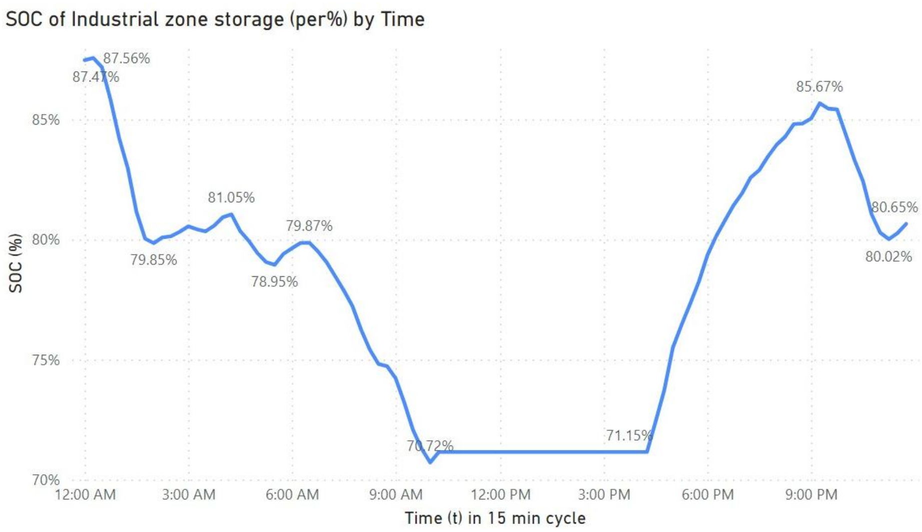

Fig. 6. SOC of storage system at industrial zone without EVs

The figure spans 24 hours, with 15-minute cycles, allowing for a comprehensive analysis of energy dynamics. The energy storage system's highest capacity is recorded at 30 000 kWh. Percentage values have been calculated based on this capacity. At the commencement of the day, the battery starts with the highest percentage, reaching 87.56%, and experiences its lowest point of 70.72% at the onset of peak hours. Different data points are intentionally provided for a more detailed and nuanced analysis, enhancing understanding and interpretation of the results.

The forthcoming results will delve into the intricate interplay of these factors, unveiling how this symbiotic amalgamation seamlessly fulfills the entirety of the industrial load. Moreover, the analysis will spotlight the noteworthy role played by V2G integration within the industrial zone, elucidating its substantial contribution to the overall energy landscape. This comprehensive exploration underscores the harmonious interaction between diverse elements, culminating in an optimized energy equilibrium that benefits both industrial operations and the integration of electric vehicles [17].

6. Results

In this section, we present the complete results of our case study using mathematical models. We delve into how the battery resources are used and provide details about the number of vehicles that were charged and discharged, all based on the mathematical model we developed. These results give us an idea of how the strategies we designed could work in theory, showing how industrial energy needs and electric vehicle operations might work together. While this analysis is based on calculations and simulations rather than actual implementation, it helps us understand the potential harmony between industry and electric vehicles in creating a balanced energy system for the future.

In the case study, an energy storage system has been integrated into the industrial zone to establish a dependable power supply during periods of high demand. As illustrated in Fig. 7, the graph underscores the system's capacity and its role in sustaining grid stability.

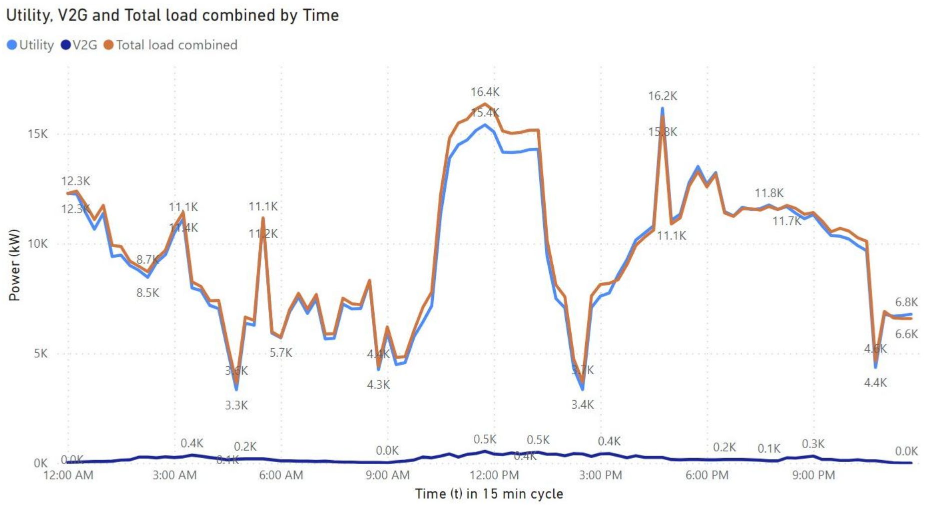

Fig. 7. Normal grid: combined load (variable load+G2V+normal industrial load) V2G, utility

The Fig. 7 illustrates that, even when combining V2G and utility power, there are times when it falls short of meeting the combined load. This is particularly evident during the concentrated demand period from 10:00 AM to 2:00 PM. Evaluating the state of charge as presented in Fig. 8 reveals the potential to fulfill the combined load and emphasizes the prospect of heightened reliance on the energy storage system. This increased dependence enhances the system's dependability and resilience, especially during high-demand intervals.

Commencing that day, the battery's SOC was registered at 26 300 kWh as percentage value 87.47%, gradually decreasing to 14 600 kWh during the peak demand period.

Nevertheless, by the day's end, the battery SOC rebounded to 18.8 kWh that is 48.74%. This evident trend vividly showcases the algorithm's efficiency in deftly managing grid equilibrium and optimizing energy storage system usage. The outcomes firmly establish the significance of integrating such systems to mitigate power fluctuations and ensure a consistent power supply throughout the day. Notably, even a high demand peak of 16 400 kWh is managed with the support of the storage system, thereby reducing strain on the utility. Various other demand peaks are also discernible throughout the daytime; however, the algorithm is designed to prioritize these peak demand periods effectively. We can see from the graph that the EVs V2G ratio is nothing but 3%–5% of complete power supplied together with utility power.

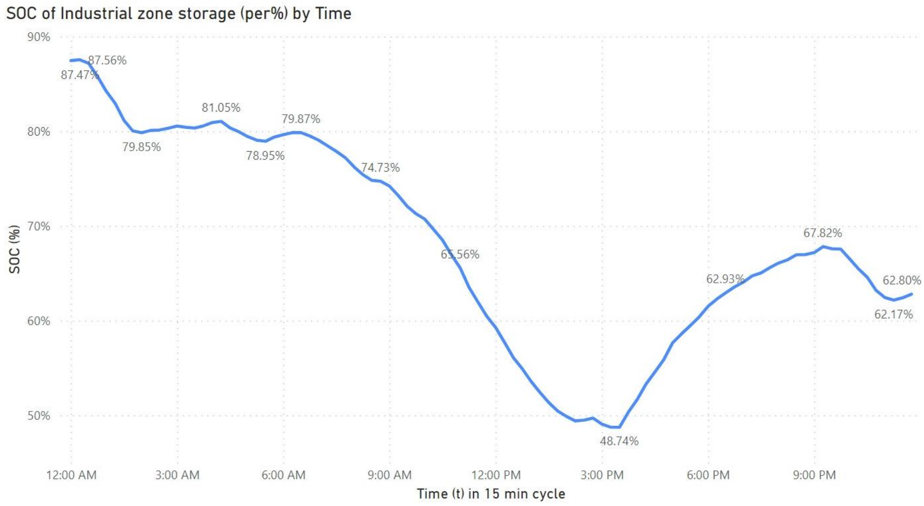

Fig. 8. Normal grid: state of charge of energy storage system at zone after supply

Figure 9 visually captures the intricate dynamics of G2V and V2G processes. A salient pattern comes to light, revealing a substantial surge in V2G activities during peak demand hours. This empirical evidence underscores the proactive role of vehicles in injecting a considerable power flow back into the grid, attaining a peak value of approximately 400 kWh. In contrast, the zenith of load encountered within the G2V context unfolds around midnight, registering at an estimated 700 kWh.

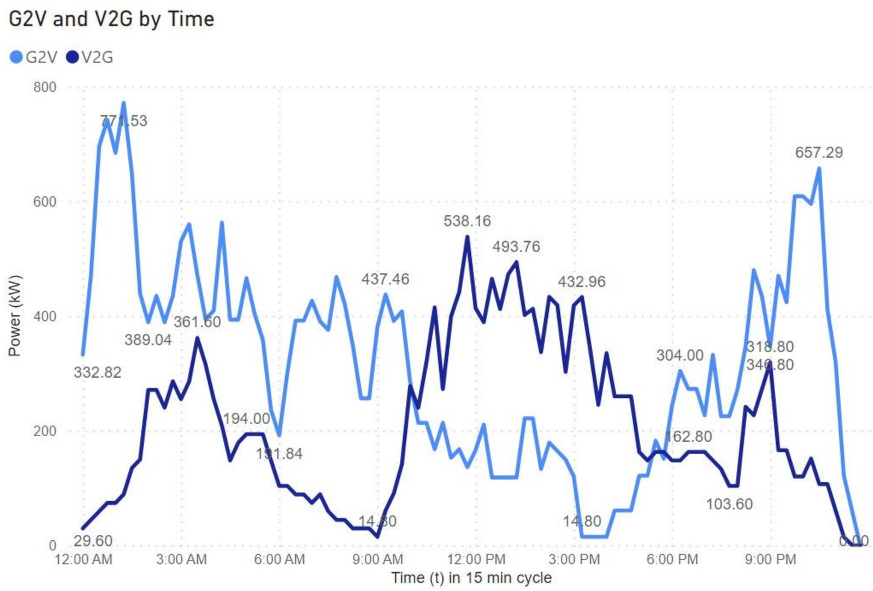

Fig. 9. Industrial load

This discernible trend speaks to a well-calibrated synergy between vehicle charging and discharging, culminating in an optimal energy management scheme. This scrutiny of interactions provides invaluable insights into the dynamic interplay of G2V and V2G activities, effectively paving the way for an enhanced understanding of vehicle-to-grid capabilities' potential. By delving into these processes, we gain a clearer comprehension of their functional dynamics, thereby advancing the strategic leverage of vehicle-to-grid mechanisms for enhanced energy efficiency and grid stability.

As presented in Fig. 9, a larger number of cars are charged during the nighttime and late evening hours, mainly due to lower electricity prices and higher power availability. This is because many industries typically operate for around 10–12 hours during the daytime. On the flip side, there is a higher occurrence of V2G operations during daylight hours, particularly during peak periods. This arrangement holds advantages for utility companies, industries, and vehicle owners alike. Utility companies and industries stand to gain from increased available power, while vehicle owners can enjoy greater returns compared to the cost of charging their cars.

Table 2 provides us with valuable insights: over the course of the entire day, a total of 126 cars undergoes charging, while 134 cars are discharged. This data reveals the dynamic ebb and flow of energy transactions within this time frame.

Table 2. No. of car charged and discharged

Car type	**Max battery size (kW)**	**Max power required to charge from zero (kW)**	**Max discharge possible from full battery (kW)**	**Amount of discharge can provide (kW)**	**Time to charge a battery (hours)**	**Time to discharge a battery (hours)**	**No. of car charge**	**No. of car discharge**
1	118.00	138.82	94.40	80.24	0.93	0.63	5	5
2	74.00	87.06	59.20	50.32	0.58	0.39	5	5
3	75.00	88.24	60.00	51.00	0.59	0.40	10	7
4	65.00	76.47	52.00	44.20	0.51	0.35	4	4
5	64.00	67.37	51.20	46.08	1.46	1.11	51	37
6	40.00	43.48	32.00	27.84	2.94	2.16	46	67
7	66	71.74	52.80	45.94	4.85	3.57	5	9
Total							126	134

It's evident that these numbers depict a continuous cycle of electric vehicle activity. Throughout the day, a selected number of cars are charged, signifying their readiness to contribute power. In parallel, a larger number of cars are discharged, reflecting the energy contribution of these vehicles back to the grid. This interplay between charging and discharging showcases the adaptable nature of electric vehicles in actively participating in the energy landscape, both as consumers and contributors.

This two-way exchange highlights the multifaceted role that electric vehicles play in balancing energy requirements and grid stability. As some cars charge up, others give back, resulting in a dynamic equilibrium that optimizes energy usage and minimizes the strain on the grid. This figure indicates that with such operation and configuration of grid EVs infrastructure is valid to install [17].

7. Conclusion

In summary, the developed management system tailored for the broader industrial zone, complemented by the incorporation of an industrial storage system and newly established EV infrastructure, has distinctly demonstrated its potential for seamless integration within the industrial zone framework. The energy storage system emerges as a pivotal component, wielding a significant role in bolstering grid stability while also laying the groundwork for forthcoming EV infrastructure advancements.

Our endeavor encompassed the utilization of diverse EV models, coupled with the deployment of three distinct charging methods within the industrial zone. This comprehensive approach aimed to acquire an optimized and practically grounded comprehension of real-world scenarios. An impressive count of 126 cars being charged and 134 undergoing discharging within a mere 24-hour time span is indeed noteworthy. This data underscores the system's efficiency in facilitating energy exchange between the grid and electric vehicles, with the interplay yielding a balanced and optimized energy ecosystem.

The algorithm presented in this paper serves as the foundation for the development of future infrastructure, particularly focusing on the integration of energy storage systems and electric vehicles (EVs). We evaluated the efficiency of the entire grid within the industrial zone by managing loads individually and in combination with various resources. The algorithm embodies a significant concept that ensures balance is maintained even in the absence of utility supply or with minimal supply. The provided graphs offer a clear understanding of load fulfillment during peak and off-peak hours.

In essence, this paper aims to establish an effective management system to address upcoming industrial challenges. It outlines the necessary steps to adapt and meet these challenges, emphasizing the importance of robust infrastructure and efficient resource utilization.

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References

[1] Elon Musk, [Online], available at: https://www.tesla.com/elon-musk, accessed 7 December 2023.

[2] Hardman S., Jenn A., Tal G., Axsen J., Beard G., Daina N., Figenbaum E., Jakobsson N., Jochem P., Kinnear N., Plötz P., Pontes J., Refa N., Sprei F., Turrentine T., Witkamp B., *A review of consumer preferences of and interactions with electric vehicle charging infrastructure*, Transportation Research Part D: Transport and Environment, vol. 62, pp. 508–523 (2018), DOI: 10.1016/j.trd.2018.04.002.

[3] Richardson P., Flynn D., Keane A., *Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems*, IEEE PES General Meeting, Minneapolis, MN, USA, pp. 1–6 (2010).

[4] Gray M.K., Morsi W.G., *Power Quality Assessment in Distribution Systems Embedded with Plug-In Hybrid and Battery Electric Vehicles*, IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 663–671 (2015), DOI: 10.1109/TPWRS.2014.2332058.

[5] Leou R.C., Su C.L., Lu C.N., *Stochastic analyses of electric vehicle charging impacts on distribution network*, IEEE Transactions on Power Systems, vol. 29, no. 3, pp. 1055–1063 (2014), DOI: 10.1109/TPWRS.2013.2291556.

[6] Faddel S., Al-Awami A.T., Mohammed O.A., *Charge Control and Operation of Electric Vehicles in Power Grids: A Review*, Energies, vol. 11, no. 4, pp. 1–21 (2018), DOI: 10.3390/en11040701.

[7] Mehta R., Srinivasan D., Khambadkone A.M., Yang J., Trivedi A., *Smart Charging Strategies for Optimal Integration of Plug-In Electric Vehicles Within Existing Distribution System Infrastructure*, IEEE Transactions on Smart Grid, vol. 9, no. 1, pp. 299–312 (2018), DOI: 10.1109/TSG.2016.2550559.

[8] Rudawski M., Fatyga K., Kwasny L., *Comparative study of DC/DC electric vehicle charging system with conventional transformer and planar transformer*, Archives of Electrical Engineering, vol. 72, no. 2, pp. 339–355 (2023), DOI: 10.24425/aee.2023.145412.

[9] Venkataswamy R., Uma Rao K., Meena P., *Transformer performance enhancement by optimized charging strategy for electric vehicles*, Archives of Electrical Engineering, vol. 71, no. 1, pp. 37–56 (2022), DOI: 10.24425/aee.2022.140196.

[10] Hilshey A.D., Hines P.D.H., Rezaei P., Dowds J.R., *Estimating the Impact of Electric Vehicle Smart Charging on Distribution Transformer Aging*, IEEE Transactions on Smart Grid, vol. 4, no. 2, pp. 905–913 (2013), DOI: 10.1109/TSG.2012.2217385.

[11] Putrus G.A., Suwanapingkarl P., Johnston D., Bentley E.C., Narayana M., *Impact of electric vehicles on power distribution networks*, IEEE Vehicle Power and Propulsion Conference, Dearborn, MI, USA, pp. 827–831 (2009).

[12] Chen X., Jiang T., Bi M., Wang Z., Gao H., *A review of condition assessment of charging infrastructure for electrical vehicles*, IET International Conference on Intelligent and Connected Vehicles (ICV 2016), Chongqing, pp. 1–4 (2016).

[13] Xia L., Mareels I., Alpcan T., Brazil M., de Hoog J., Thomas D.A., *A distributed electric vehicle charging management algorithm using only local measurements*, ISGT 2014, Washington, DC, USA, pp. 1–5 (2014).

[14] Marcincin O., Medvec Z., Moldrik P., *The impact of electric vehicles on distribution network*, 18th International Scientific Conference on Electric Power Engineering (EPE), Kouty nad Desnou, Czech Republic, pp. 1–5 (2017).

[15] Morsalin S., Mahmud K., Town G., *Electric vehicle charge scheduling using an artificial neural network*, IEEE Innovative Smart Grid Technologies – Asia (ISGT-Asia), Melbourne, VIC, Australia, pp. 276–280 (2016).

[16] Holcsik P., Pálfi J., Čonka Z., Kocsis I.B., *Fault Point Location Method, Based on Harmonics Analysis of a Distribution System*, Acta Polytechnica Hungarica, vol. 19, no. 4, pp. 147–164 (2022), DOI: 10.12700/APH.19.4.2022.4.8.

[17] Tailor R., *Design of Smart Network in Industrial Zone*, PhD Thesis, Department of Electric Power Engineering, Technical University of Kosice, Kosice (2023).