中国光储直柔建筑发展战略路径研究

（二期）

Research on the Strategic Path of PEDF Buildings in China (Phase II)

子课题 5：电动车与建筑协同参与电网调节的潜力与模式研究

Task 5：Research on the Energy Flexibility Potential of Coordinating Electric Vehicles and Buildings for Grid Regulation

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执行摘要

1. 建筑领域节能减碳面临新挑战

- **低碳发展已是全球共识。**至今全球已有 170 多个国家签署《巴黎协定》，确定了未来全球温升控制在低于 2 度且尽可能争取 1.5 度的奋斗目标。中国作为碳排放大国，积极推动低碳事业的发展，习近平总书记在第 75 届联合国大会上提出中国力争在 2030 年前实现碳达峰，2060 年前实现碳中和的目标。尤其在当下全球经济增速放缓，经济绿色复苏备受关注。

- **分布式风光电广泛应用。**可再生电力能源是实现低碳减排的重要支撑，预计2030 年我国并网风电光电的发电装机容量将达到 12 亿 kW 以上，至 2060 年我国风电和光电的装机容量甚至将达到 60 亿 kW 以上。风电光电提供的电量则要从目前的不到 10%增加到 60%左右。但风电和光电都需要巨大的安装面积。因此，以分散的建筑外表面、零星空地等为基础的分布式风光电将成为未来可再生电力供给的重要组成部分。

- **建筑交通用能紧密关联。**建筑和交通领域是能源消耗的两个重要场景，建筑领域相关用能约占社会总能耗的 1/3，而预计 2030 年，中国将保有约 8000 万辆电动汽车，增加 20%的区域电耗。同时，两个领域都是用能的终端场景，具有很大的柔性潜力。两者有很紧密的联系，电动汽车约有 80%以上的时间都是停留在建筑周边，其中以办公和住宅两种场景为主。在低碳发展的背景下，建筑和交通领域将形成更加紧密的关联。

- **电网系统面临巨大挑战。**由于“双高”特性，即间歇性可再生能源的高渗透和低惯性电力电子比例高，未来电力系统将面临能量不平衡差距扩大和惯性稳定性下降的问题，对城市能源系统的安全可靠性构成严峻挑战。提高建筑能源的灵活性，挖掘电动汽车蓄能和可调节潜力是应对这一挑战、实现城市能源系统可持续发展的关键，逐渐成为除能效提升外的节能新维度。

2. 城市私家车行为特征研究

- **私家电动车转移及停留行为。**由于人行为的流动特点，私家车(占总车辆的 80%以上)在其生命周期的 90%以上的时间都停在建筑停车场及周边。北京市研究案例表明，私家车辆 60%以上时间停留在其长期停留的住宅或办公建筑内。电动汽车的充电负荷与建筑物的充电负荷是密不可分。

- **私家电动车充电需求时空分布。**随着城市内电动汽车数量的不断增长，电动汽车的额外能源需求对电网负载带来新的挑战。电动汽车的能源需求在一天中的分布非常不均，夜晚大多数人的居家充电行为容易导致充电高峰，对电网负载造成冲击。本项目基于 MOCC 系统的行为模拟结果，刻画了一天中深圳市私家电动汽车充电行为形成的时空负载分布。车辆充电负载有 85%以上发生在住宅及办公建筑内。

- **私家电动车充电给电网同时带来机遇与挑战。**基于 MOCC 系统的行为模拟结果表明，当车辆完全电动化时，电动汽车不受控充电峰值负载对电网将造成8.5%~13.4%的负荷波动。但对车辆充电进行调控，平均每辆电动汽车可以提供其总电池容量的近 70%为城市能源管理使用，可大大减少电网储能投资。

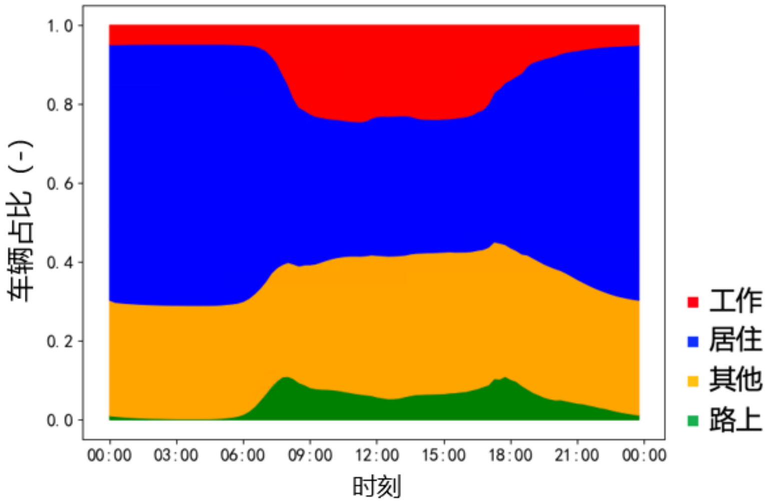


图 1 北京市私家车辆全天停留位置分布

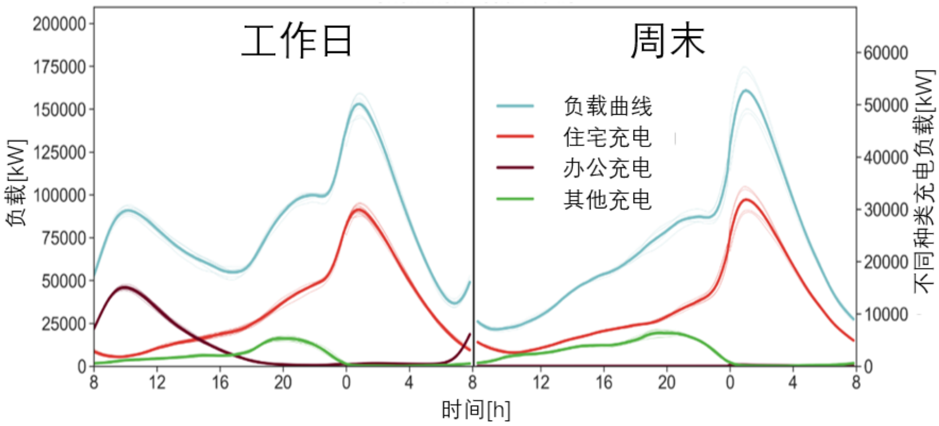


图 2 深圳市电动汽车充电负载逐时分布

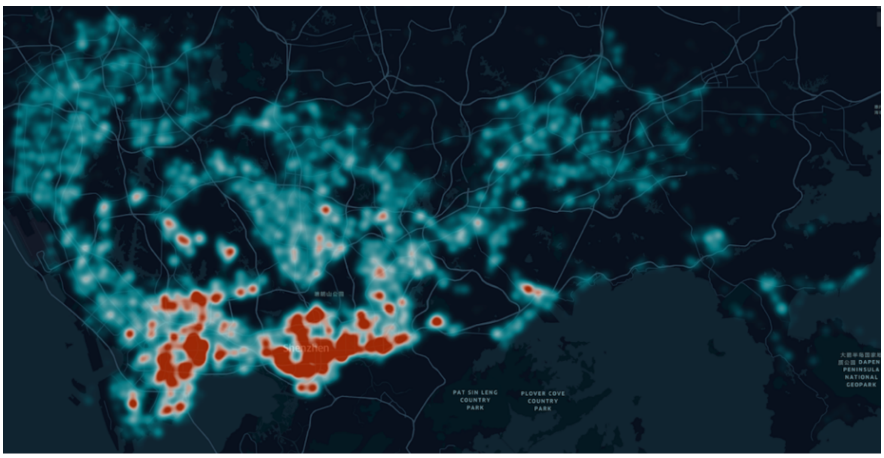


图 3 深圳市电动汽车充电负载空间分布

3. 电动汽车与建筑智慧互动促进节能增效

- **建筑尺度：智能有序充电促进光伏自消纳。**目前主导的“即接即充”、“快充为主”模式对城市电网造成冲击，并且无法有效利用建筑光伏。采用智能有序充电策略，为私人电动汽车提供间歇性但免费的太阳能充电服务，可满足其日常城市内交通需求，同时无需储能电池即可协调光伏发电和车充电负荷，使得系统的年光伏自消纳率从 33.3%提高到 67.9%，与传统太阳能充电站相比，折现投资回收期可以从 9.4 年减少到 4.5 年。

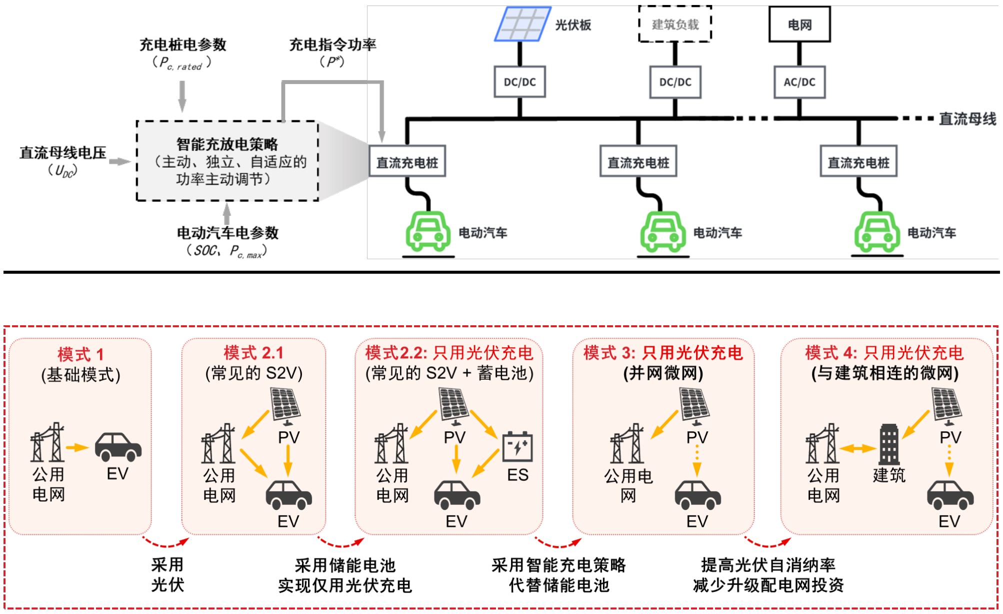


图 4 建筑光伏智能充电系统与不同模式

- **区域场景：车网互动发挥降本节能潜力。**农村采暖清洁化转型背景下，农村光伏快速发展，电动汽车快速普及。基于车网互动的电采暖系统可成为解决乡村地区光伏消纳，电采暖问题的有效途径。采用 V2H 模式，光伏发电的电采暖系统配网扩容容量降低 45.9% ，用户电费降低 68.5%，并可完成光伏的内部消纳。

- **城市尺度：车辆与建筑互动实现互补。**未来电力系统下车辆与建筑协同参与电网调节，电动汽车拥有冗余电池容量，可将车辆作为其停留建筑的等效储能资源，建筑拥有冗余的配电容量，在大幅缓解城市低压配电网增容压力的同时能够增强需求侧的柔性调节能力。结果表明，利用建筑冗余配电可满足车辆慢充需求；根据建筑负载对车辆充放电进行调控，可有效转移车辆充电时段有效降低建筑和车辆负载峰谷差，有序单向充电可降低 22.3%，双向充电可降低 57.4%。

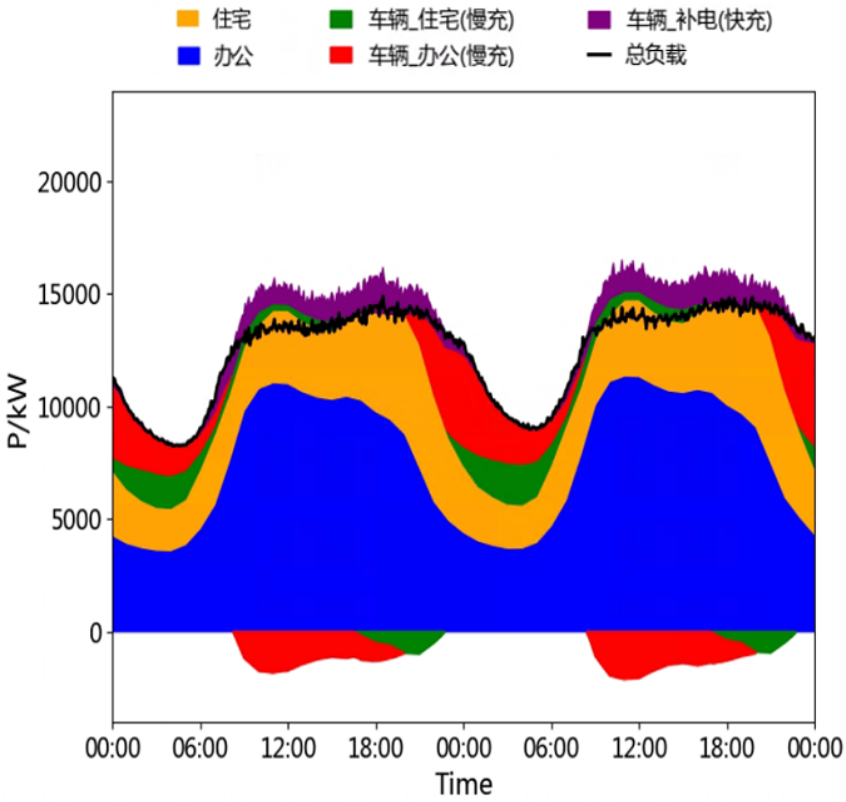


图 5 有序充放模式下车辆与建筑负载分布

表 1 不同车辆与建筑互动模式下需求侧负载峰谷差

充电模式	是否利用建筑配电	日均峰谷差/kW	负载降低比例/%
无序充电	否	10831.9	0
有序充电	否	6960.3	35.7
有序充放	否	5213.0	51.9
无序充电	是	10831.8	0
有序充电	是	6960.3	35.7
有序充放	是	5213.0	51.9

4. 智能充电系统的运营模式与运营效果

- **利用峰谷电价差带来足够收益，电池寿命可满足使用需求。**为挖掘车载电池潜力参与电网调节，采用"免费充电，统一调度"模式：使建筑配电网在电力负荷低谷时段为车充电、建筑从车取部分电满足高峰用电需求，可解决私家车辆日常城内出行和部分建筑高峰用电需求，同时从峰谷电价差中获益。180 辆电动汽车一年可以转移电力 64.2 万 kWh，产生收益 36.9 万元，其中充电桩建设的投资回收期少于 4 年。并且电动汽车的电池寿命由 9.6 年增长至 11.1 年，满足电动汽车的使用年限需求。

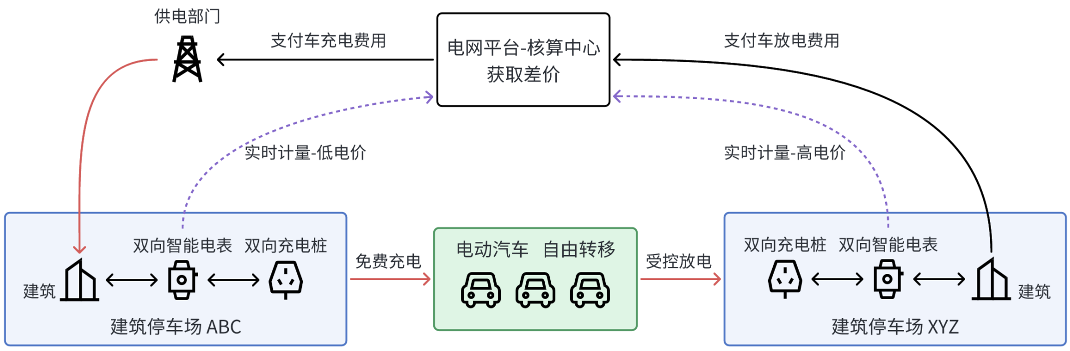


图 6 "免费充电，统一调度"模式示意

- **利用会员制服务模式激励用户参与调节。**为鼓励电动汽车车主参与智能充电系统，通过问卷调查收集用户意愿，进而设计出对用户最具备激励作用的充电服务。对满足条件的会员用户免费提供洗车服务、抛锚急救服务，并以贡献积分提升其荣誉感。使得 44.63%的被测用户愿意选择对电动车充电行为限制较大的模式。
- **智能充电模式可有效促进光伏利用。**基于所提出的会员制模式，利用电动车电池作为储能，分析电动汽车与建筑协同参与电网调节这一模式对光伏消纳的作用。计算结果表明，通过可控充放电，能够有效利用电动汽车的移动性，在住宅场景下和办公室场景下分别增加了 57%和 52%的总光伏发电的利用率。

5. 电动汽车与建筑智慧互动的工程示范

- **建筑尺度：北京市清华大学建筑节能楼。**将所提出的智能有序充电策略应用于实际系统，利用智能充电桩很好地将光伏发电与电动汽车充电匹配，实现 100%利用光伏充电。相比传统恒功率充电模式，将光伏自消纳率提高了 89%，将光伏最大并网功率下降了 42%，有效减少了光伏并网压力。

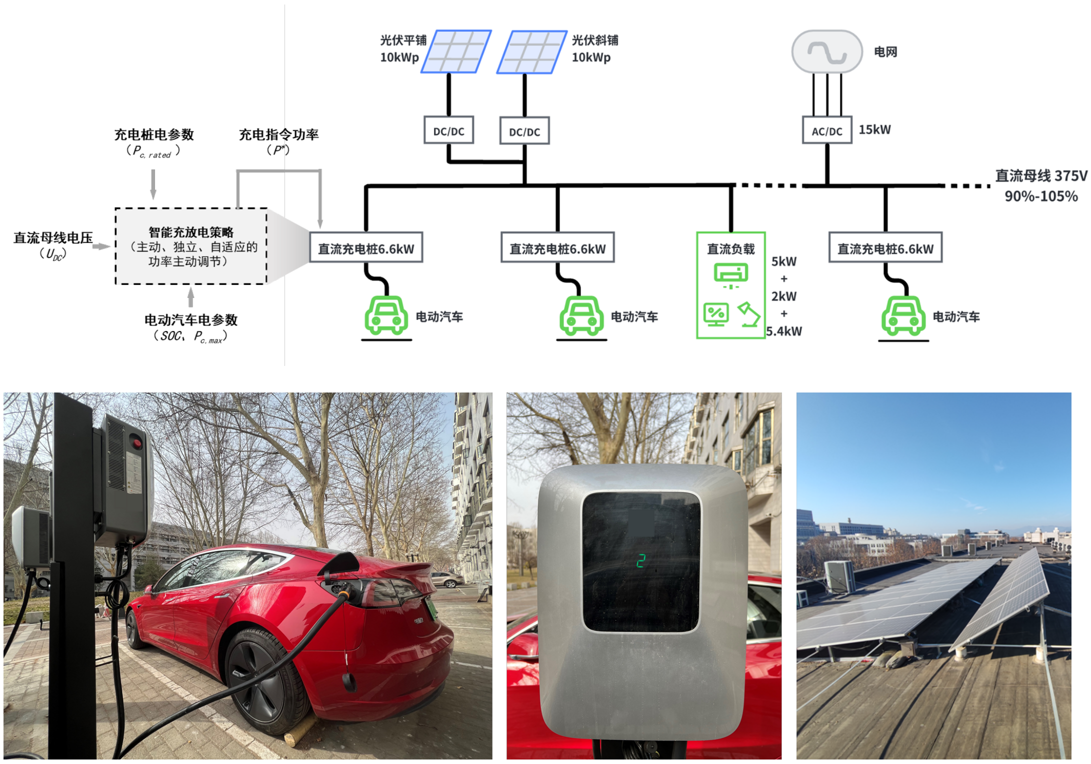


图 7 系统拓扑结构及组件示意

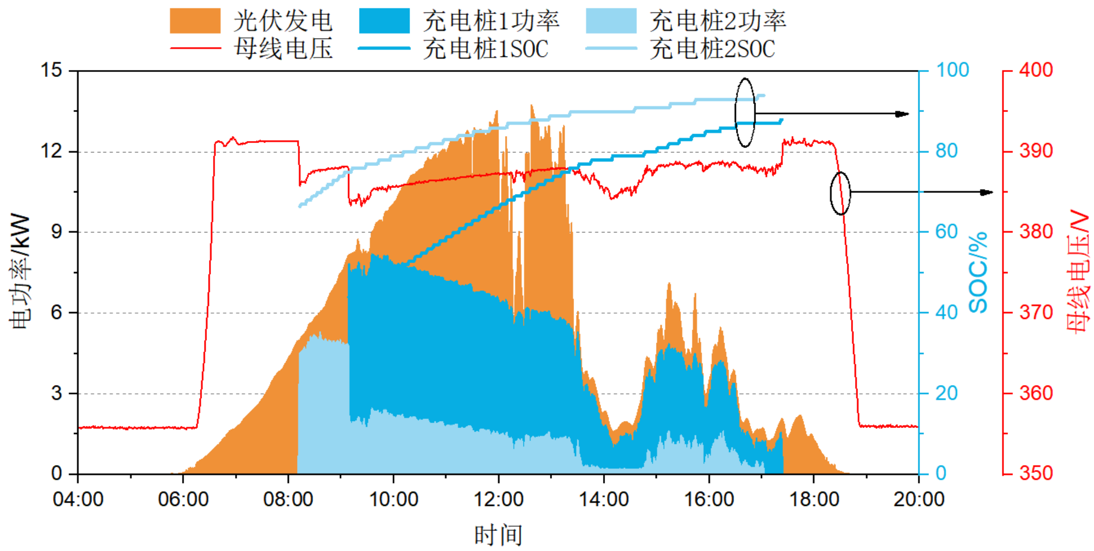


图 8 实际系统实现对充电功率的精准控制

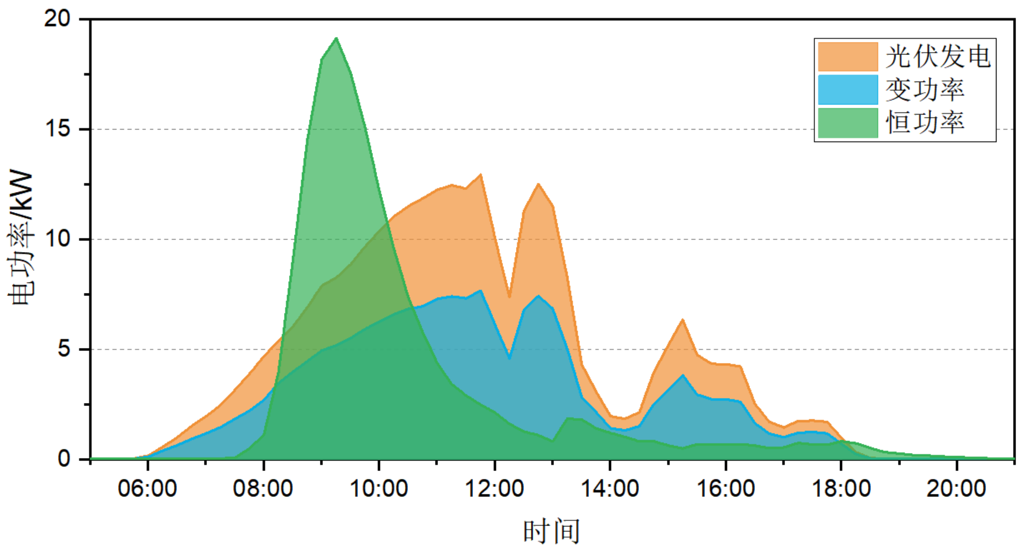


图 9 智能有序充电模式能有效匹配光伏发电和车充电负荷

- **建筑尺度：深圳市某绿色产业园区办公楼。**构建实际“光储直柔”系统建筑，研究直流配电建筑中多支路负载的运行表现和各支路负载的能量损耗情况，进行系统整体与各支路能量效率的计算，通过机器学习的方法对影响用能效率的相关性因素进行了分析。实际运行结果表明，直流配电系统与交流配电系统相比表现出了明显效率提升。

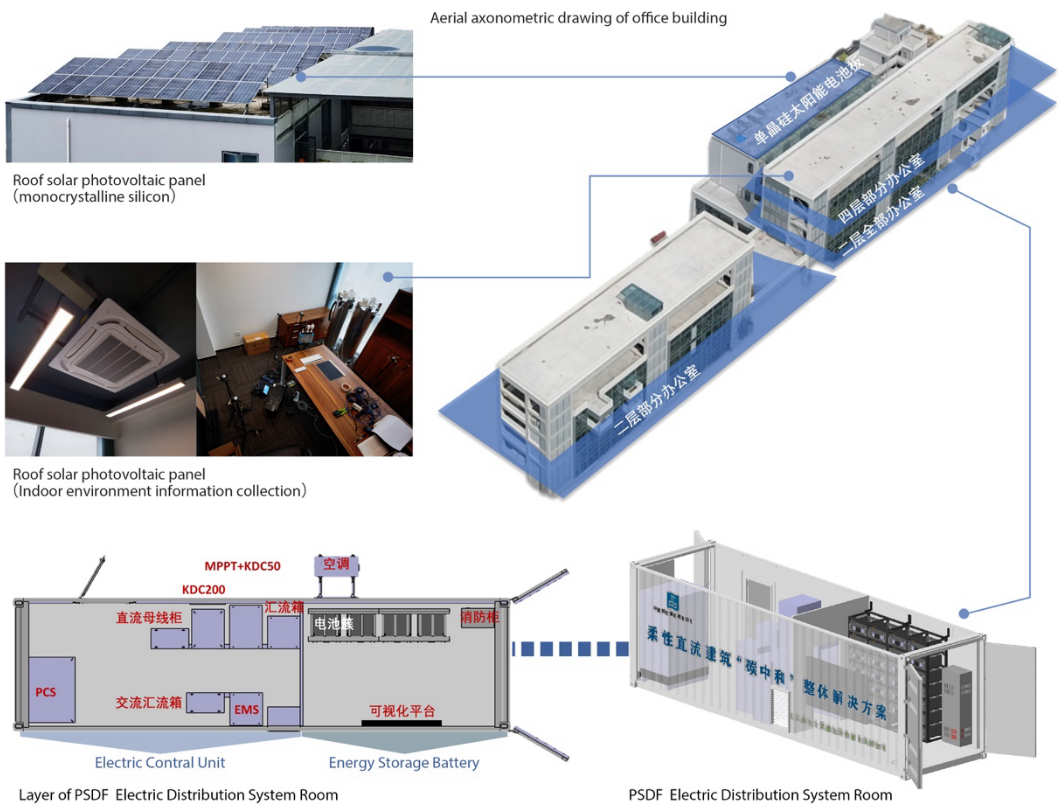


图 10 光储直柔办公楼总览

- **区域尺度：基于北京厂房改建项目的区域级项目规划。**北京市 1201 厂房计划

改造为办公楼，结合智能充电桩系统对其进行规划。对该园区不加额外储能的模式下，光伏自消纳率可有效提升：当该园区有 60 辆电动汽车参与互动时，光伏自消纳率可以达到 86.3%；当该园区有 200 辆电动汽车参与互动时，光伏自消纳率可以达到 90.6%

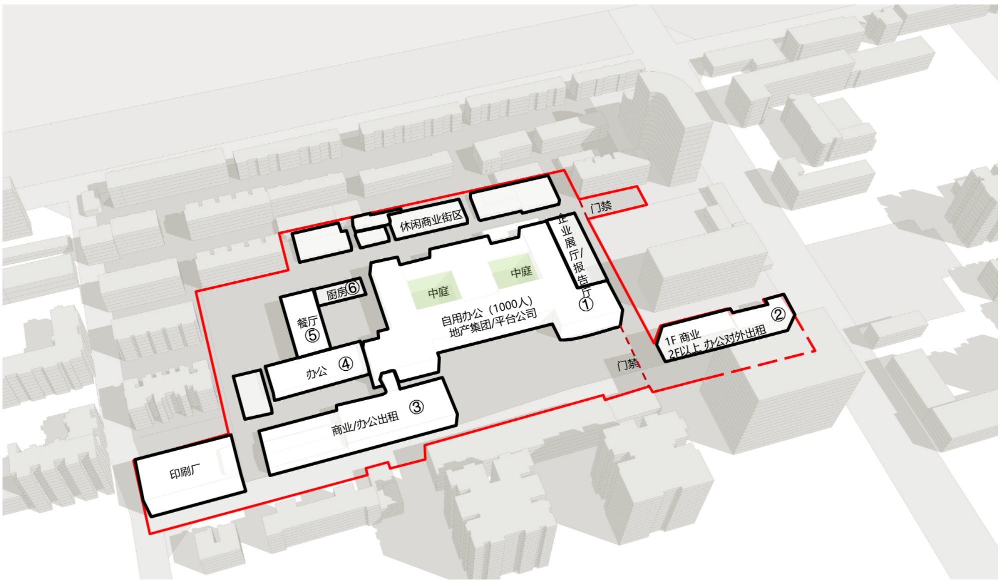


图 11 厂房改造为办公建筑的区域示意

- **城市尺度：基于深圳市的城市级能耗仿真模拟。**以深圳市为例探索城市规模尺度下电动车与建筑协同用能对城市能源系统的影响，基于深圳市 57 万栋建筑以及 48 万辆电动车的真实数据构建城市级能耗仿真模拟器。结果表明，利用电动车储能，可以使深圳市的光伏消纳率从 76%提升到 90%，随着电动车数量的增多，光伏消纳率还可以进一步提升。

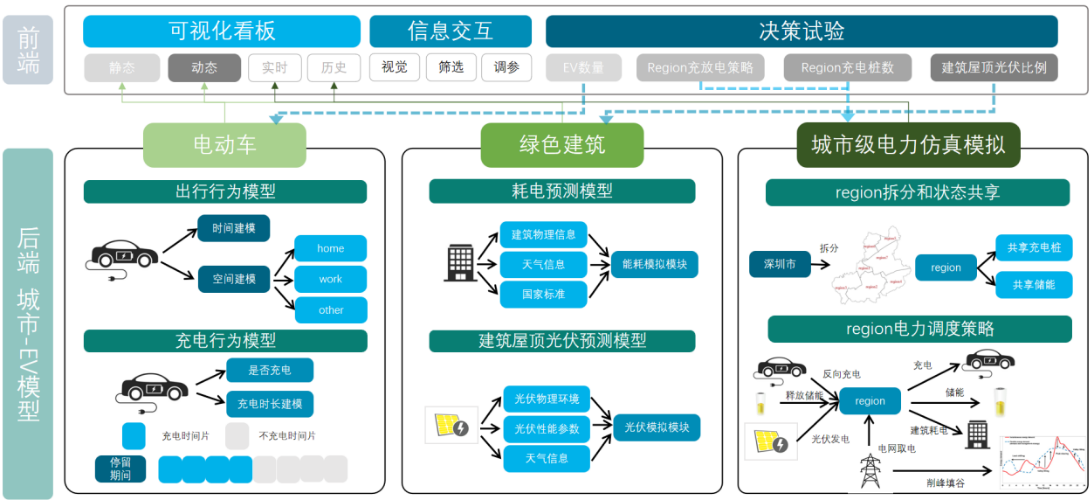


图 12 城市级能耗仿真模拟器

Executive Summary

1. Building sector faces significant energy efficiency and carbon reduction challenges

- **The global consensus now revolves around low-carbon development.** Over 170 countries have signed the Paris Agreement, committing to limiting global warming to below 2°C, with a goal of achieving 1.5°C. China, a major carbon emitter, is actively promoting low-carbon initiatives. General Secretary Xi Jinping announced at the 75th United Nations General Assembly that China aims to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. This commitment is especially noteworthy in the context of the current global economic slowdown and the increasing focus on green economic recovery.

- **Distributed wind and solar power are widely adopted to support low-carbon emissions.** By 2030, China aims to have over 1.2 billion kW of grid-connected wind and solar capacity, and potentially exceed 6 billion kW by 2060. These sources are expected to provide around 60% of the electricity, up from less than 10%. Distributed wind and solar power, utilizing building surfaces and open spaces, will play a crucial role in future renewable energy supply.

- **Building energy use and transportation are closely linked.** Both sectors are major energy consumers, with buildings accounting for about one-third of total energy consumption. By 2030, China is expected to have approximately 80 million electric vehicles, increasing regional electricity demand by 20%. Electric vehicles spend over 80% of their time near buildings, mainly in office and residential areas. In the context of low-carbon development, these sectors will have a closer relationship.

- **The power grid faces significant challenges.** Because of the rise of intermittent renewable energy sources and reduced power system stability. This poses a serious challenge to urban energy systems. To address this, increasing building energy flexibility and utilizing electric vehicle energy storage become key solutions for sustainable urban energy systems, adding a new dimension to energy efficiency.

2. Study on Behavior of Urban Private Electric Vehicles

- **Private EVs transfer and parking behavior.** Due to the mobility patterns of individuals, private cars (accounting for over 80% of the total vehicles) spend over 90% of their lifecycle parked in and around buildings. A research case in Beijing suggests that private vehicles spend more than 60% of their time parked in their long-term residential or office building locations. The charging demand of electric cars is closely intertwined with the charging load of buildings.

- **Temporal and spatial distribution of private EV charging demand.** With the continuous growth in the number of electric vehicles within cities, the additional energy demand from electric cars poses new challenges to the power grid load. Electric vehicle energy demand is highly unevenly distributed throughout the day, with most people charging their vehicles at home during the night, leading to charging peaks that impact the power grid load. Based on the behavior simulation results from the MOCC system, this project depicts the temporal and spatial load distribution of private electric vehicle charging behavior in Shenzhen. More than 85% of vehicle charging load occurs in residential and office buildings.

- **Private EVs charging presents both opportunities and challenges to the power grid.** Based on behavior simulation results from the MOCC system, it is shown that when vehicles are fully electrified, uncontrolled charging peak loads from electric vehicles can cause fluctuations of 8.5% to 13.4% in the power grid load. However, by regulating vehicle charging, each electric vehicle can contribute nearly 70% of its total battery capacity for urban energy management, significantly reducing the need for grid energy storage investments.

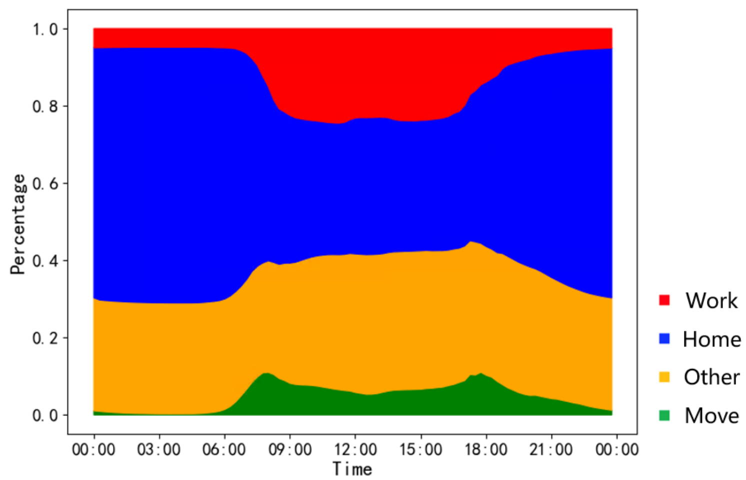


Figure 1 All-Day Parking Location Distribution of Private EVs in Beijing

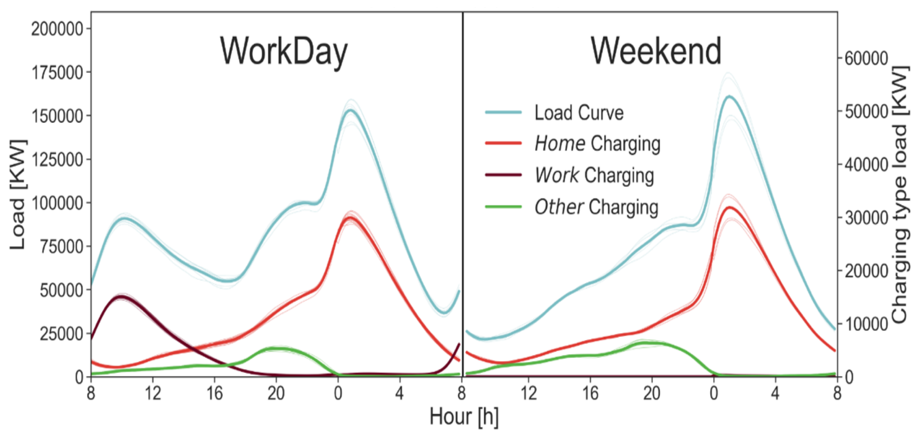


Figure 2 Hourly Distribution of Electric Vehicle Charging Load in Shenzhen.

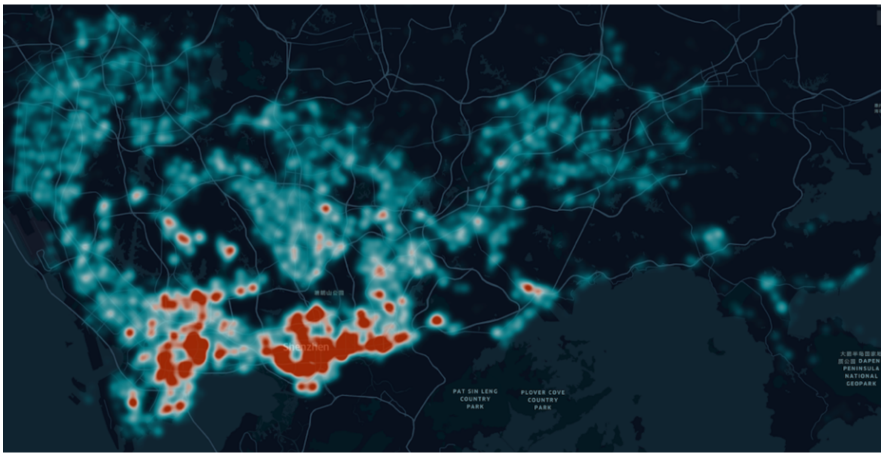


Figure 3 Spatial Distribution of Electric Vehicle Charging Load in Shenzhen.

3. Efficient collaboration between electric vehicles and buildings promotes energy savings

- **Building Scale: Smart and orderly charging promotes photovoltaic self-consumption.** Current 'plug-and-charge' methods strain urban grids and underutilize building solar energy. Implementing smart, intermittent solar charging for private EVs not only meets daily urban commuting needs but also enhances photovoltaic self-consumption from 33.3% to 67.9%. This reduces the investment payback period from 9.4 to 4.5 years.

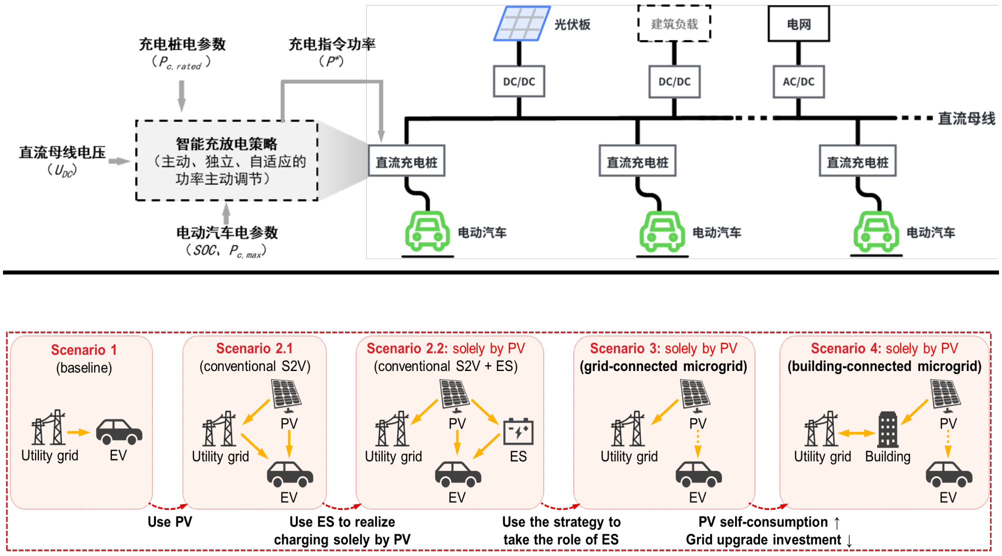


Figure 4 Building photovoltaic intelligent charging system and different modes

- **Regional Scale: Vehicle-grid interaction promotes cost savings and energy efficiency.** In the transition towards cleaner rural heating, rural photovoltaics are rapidly growing, along with the widespread adoption of electric vehicles. Leveraging vehicle-grid interaction for electric heating systems can effectively address photovoltaic integration and electric heating challenges in rural areas. Using the V2H (Vehicle-to-Home) model, the capacity expansion required for photovoltaic electricity is reduced by 45.9%, user electricity costs decrease by 68.5%, and internal photovoltaic consumption is achieved.

- **Urban Scale: Vehicle and Building Interaction for Mutual Benefits.** In the future electricity system, vehicles and buildings will collaboratively participate in grid regulation. Electric vehicles will possess surplus battery capacity, enabling them to serve as equivalent energy resources for the buildings in which they are parked. Buildings, in turn, will have redundant distribution capacity, significantly alleviating the pressure to expand the city's low-voltage distribution grid while enhancing demand-side flexibility. The results indicate that utilizing building's surplus distribution capacity can meet the slow charging demands of vehicles. By controlling vehicle charging and discharging based on building loads, it is possible to effectively shift the time of vehicle charging, reducing the peak-to-valley difference in both building and vehicle loads. V1G charging mode can reduce this difference by 22.3%, while V2G charging mode can reduce it by 57.4%.

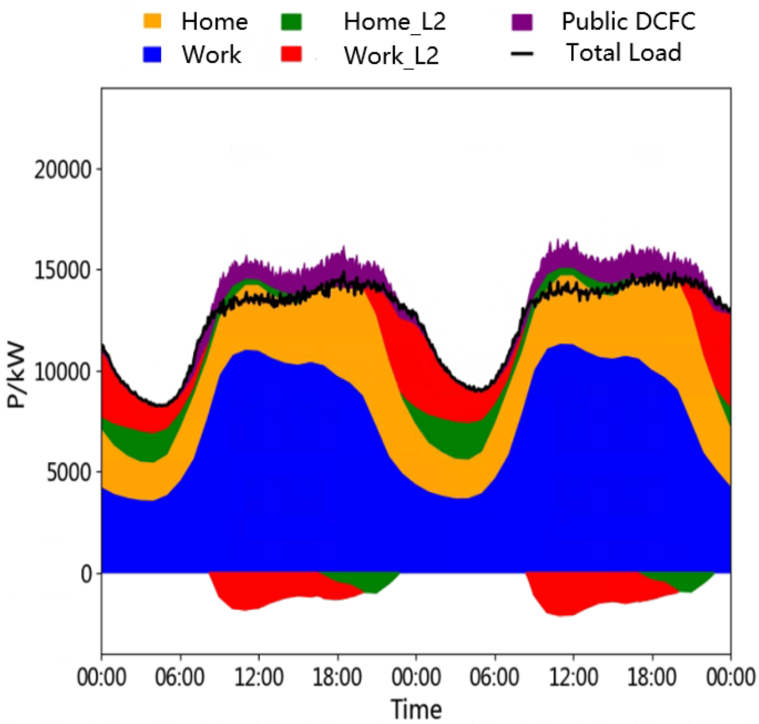


Figure 5 Vehicle-to-Grid (V2G) Mode: Distribution of Vehicle and Building Loads.

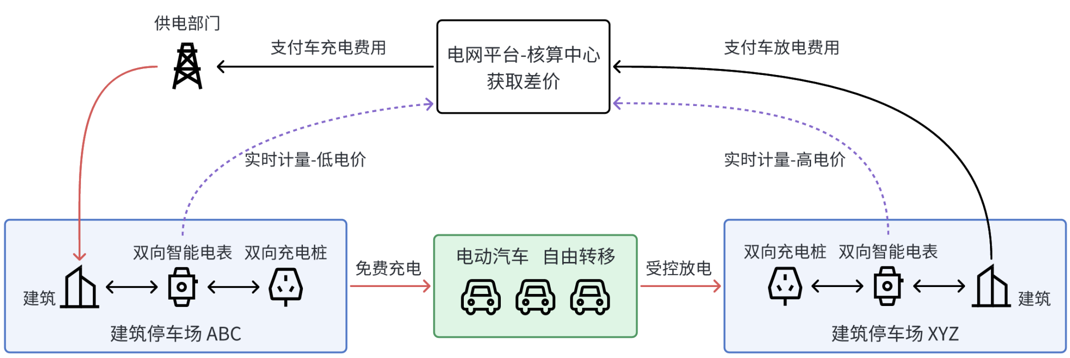
Table 1 Peak-to-Valley Differences under Different Vehicle and Building Interaction Modes.

Charging Mode	Utilization of Building Distribution systems	Daily Peak-to-Valley Difference (kW)	Load Reduction Percentage (%)
V0G	No	10831.9	0

V1G	No	6960.3	35.7
V2G	No	5213.0	51.9
V0G	Yes	10831.8	0
V1G	Yes	6960.3	35.7
V2G	Yes	5213.0	51.9

4. The operational modes of smart charging systems.

- **Utilizing the price difference between peak and off-peak electricity hours can generate sufficient revenue while preserving battery life.** To tap into the potential of vehicle batteries for grid regulation, the 'free charging, unified scheduling' model is adopted. This mode allows building distribution grids to charge vehicles during low-demand periods and draw power from vehicles to meet peak electricity needs. It addresses daily urban commuting and some building peak electricity demands while capitalizing on peak-off-peak price differences. 180 electric vehicles can transfer 642,000 kWh of electricity annually, generating revenue of 369,000 yuan. The investment payback period for charging stations is less than 4 years, and electric vehicle battery life extends from 9.6 to 11.1 years.



- Figure 6 schematic diagram of the "free charging, unified dispatch" mode

- **Using a membership-based service model to incentivize user participation in grid regulation.** To encourage electric vehicle owners to engage with the smart charging system, user preferences were collected through surveys. This data was then used to design the most appealing charging services. Eligible members receive complimentary car washes and roadside assistance, and their contributions are rewarded with loyalty points. As a result, 44.63% of surveyed users are willing to choose a mode with more restrictions on EV charging behavior.

- **The smart charging model effectively enhances photovoltaic utilization.** Using the proposed membership-based approach and electric vehicle batteries as energy storage, the impact of electric vehicles and buildings participating together in grid regulation on photovoltaic integration was analyzed. The results show that through controllable charging and discharging, leveraging the mobility of electric vehicles increased total photovoltaic generation utilization by 57% in residential settings and 52% in office settings.

5. Engineering Demonstrations of Smart Interaction between Electric Vehicles and Buildings

- **Building Scale:** Tsinghua University's Energy-Efficient Building in Beijing. The proposed smart and orderly charging strategy was implemented in a real-world system. It effectively matches photovoltaic generation with electric vehicle charging using smart charging stations, achieving 100% utilization of solar charging. Compared to traditional constant power charging, this approach increased photovoltaic self-consumption by 89% and reduced maximum photovoltaic grid connection power by 42%, effectively alleviating grid pressure from photovoltaic integration.

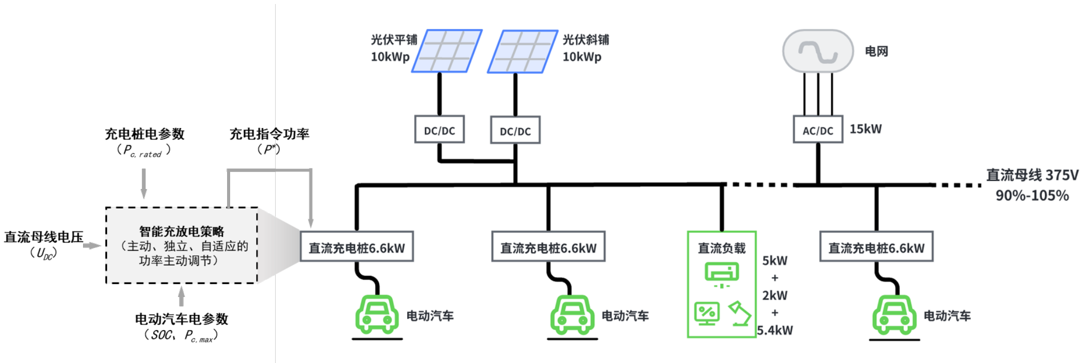
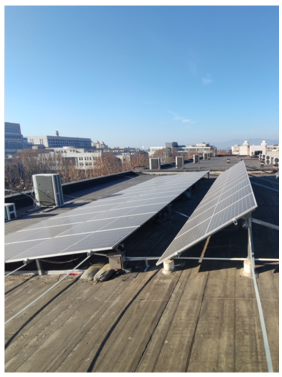


Figure 7 System topology and component diagram

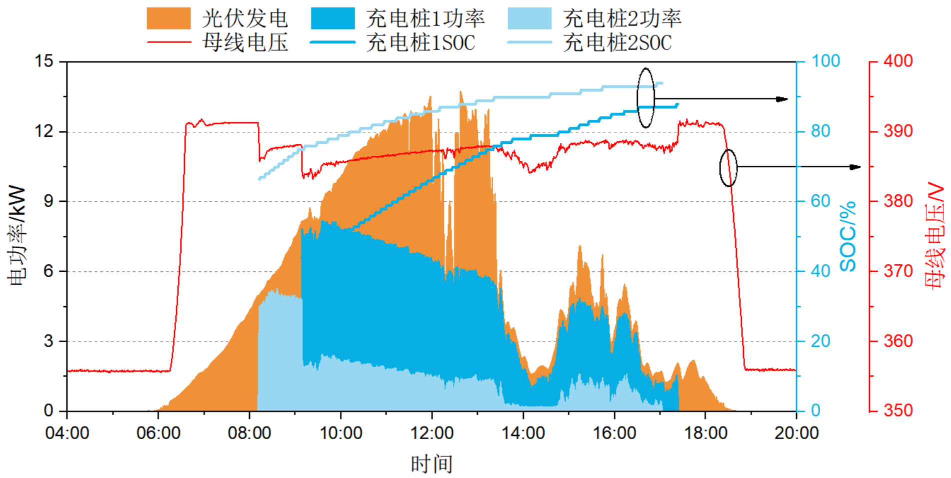


Figure 8 Accurate control of charging power in actual system implementation

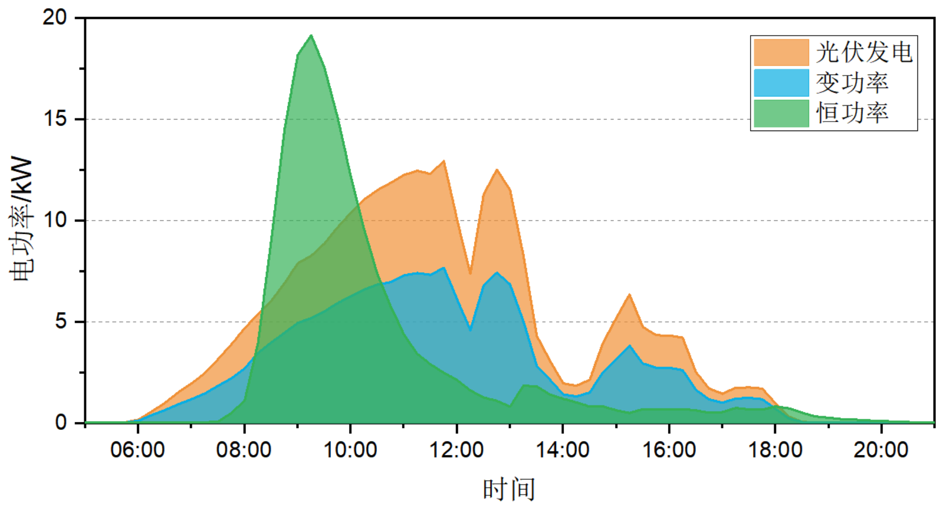


Figure 9 Intelligent orderly charging mode can effectively match photovoltaic power generation and vehicle charging load

- **Building Scale: Office building in a green industrial park in Shenzhen.** We constructed a practical 'PSDF' building system, studied the performance of multiple branch loads in DC distribution buildings, assessed energy losses in each branch load, and calculated the overall system and branch-level energy efficiency. We analyzed factors influencing energy efficiency using machine learning methods. Actual operational results demonstrated a significant efficiency improvement in the DC distribution system compared to the AC distribution system.

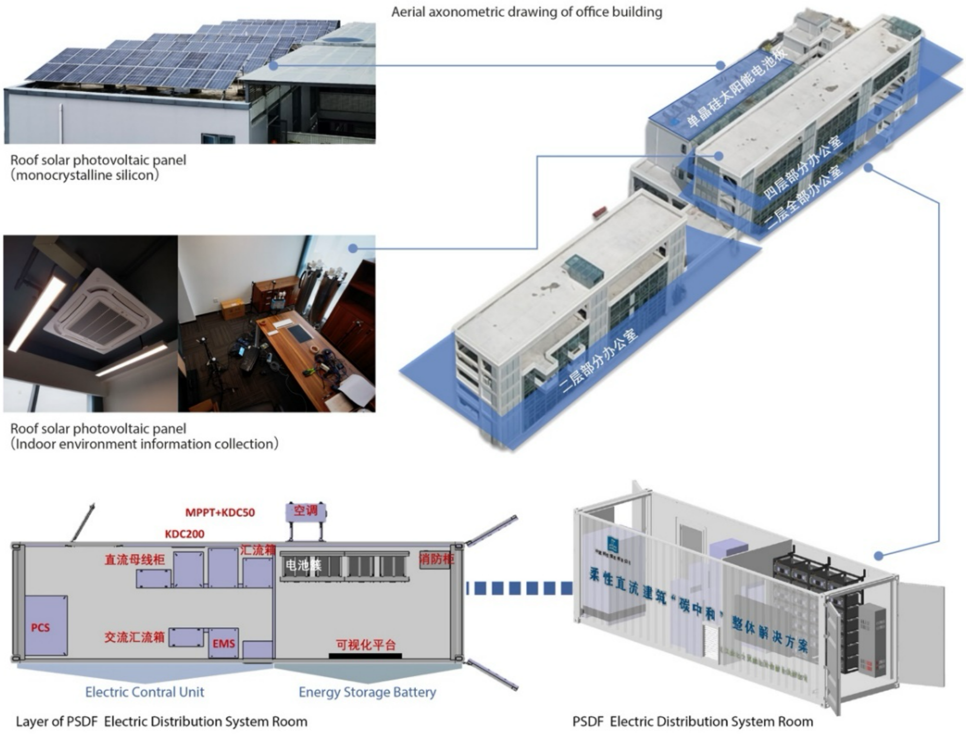


Figure 10 General view of office building with PEDF power supply

- **Regional Scale: Project planning based on the conversion of Factory 1201 in Beijing.** The plan involves transforming Factory 1201 in Beijing into an office building, incorporating an intelligent charging station system. Without additional energy storage, the photovoltaic self-consumption rate in this park can be significantly improved. When 60 electric vehicles participate in the interaction, the photovoltaic self-consumption rate can reach 86.3%. With 200 electric vehicles participating, it can reach 90.6%.

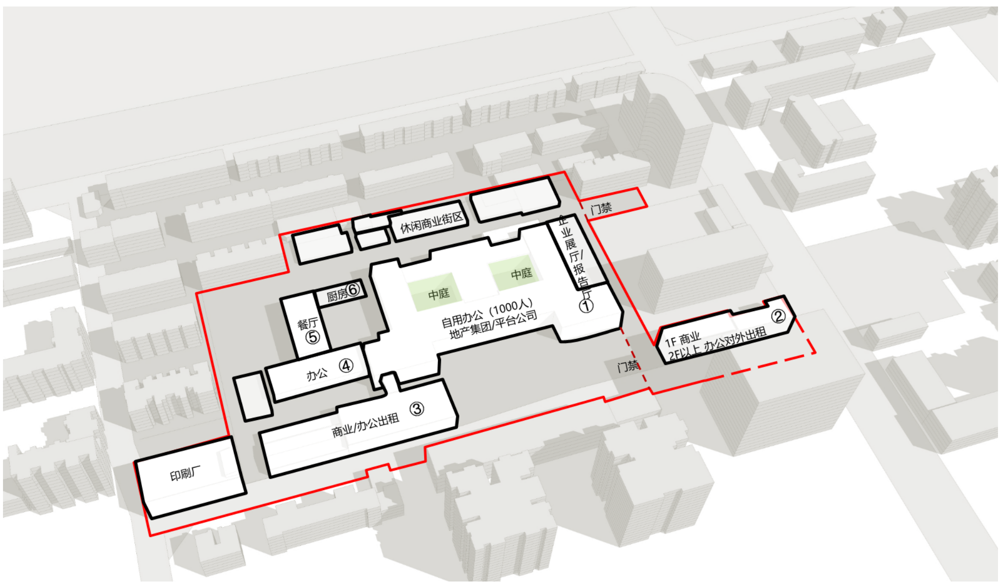


Figure 11 Area schematic diagram of the conversion of plant building into office buildings

- **City Scale: Urban energy consumption simulation based on Shenzhen.** Using Shenzhen as a case study, we explored the impact of coordinated energy use between electric vehicles and buildings on the city's energy system. We constructed a city-level energy consumption simulator based on real data from 570,000 buildings and 480,000 electric vehicles in Shenzhen. The results show that utilizing electric vehicle energy storage can increase Shenzhen's photovoltaic integration rate from 76% to 90%, with the potential for further improvement as the number of electric vehicles increases.

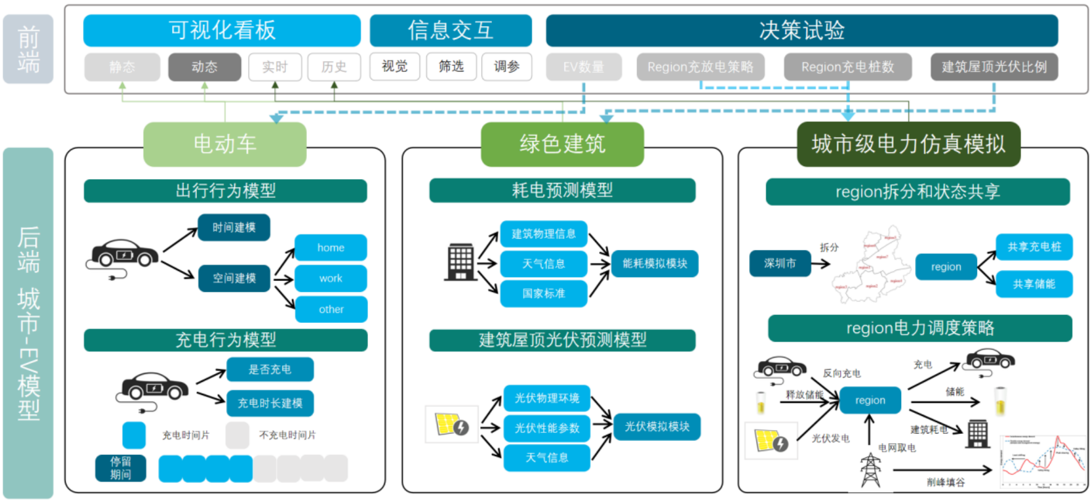


Figure 12 Simulation simulator of energy consumption at the city level