Integrating Electric Vehicle Charging Infrastructure into Commercial Buildings and Mixed-Use Communities: Design, Modeling, and Control Optimization Opportunities

Preprint

Shanti Pless, Amy Allen, Lissa Myers, David Goldwasser, Andrew Meintz, Ben Polly, and Stephen Frank

National Renewable Energy Laboratory

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Integrating Electric Vehicle Charging Infrastructure into Commercial Buildings and Mixed-Use Communities: Design, Modeling, and Control Optimization Opportunities

Shanti Pless, Amy Allen, Lissa Myers, David Goldwasser, Andrew Meintz, Ben Polly, and Stephen Frank, National Renewable Energy Laboratory

ABSTRACT

Many cities and states have aggressive goals for personal and fleet vehicle electrification. For example, the City and County of Denver set a goal of 30% of vehicles being electric by 2030, growing to 100% in 2050. Reaching ambitious goals like this will require significantly more charging stations at workplaces, homes, apartments, and public fast charging stations. Charging infrastructure build-out is directly linked with electric vehicle (EV) uptake, and smart EV charging infrastructure planning, electrical system integration, new building electrical codes, and demand management are presenting new integration concepts and challenges for building owners, utilities, and designers.

This paper discusses modeling and field studies of controlled EV charging that have been performed with the goal of minimizing requirements for infrastructure upgrades, minimizing building peak demand charges, and maximizing the use of on-site generation. We present a large-scale workplace charging pilot of a demand-controlled scheduled EV charging system with over 250 active daily commuters, successfully demonstrating management of aggregate charging power to avoid new infrastructure investments, mitigate peak demand charges, and provide cost-effective workplace charging to users. In addition to understanding opportunities for demand management, integrating these controllable loads into the energy modeling process for new buildings will also be necessary. This paper then presents an example energy modeling process that evaluates the potential effects of EV charging on building load profiles and infrastructure requirements for a mixed-use community. Finally, we discuss an illustration of how EV charging can be controlled to be synergistic with other building loads and distributed generation.

Background

Many cities and states have aggressive goals for personal and fleet vehicle electrification. Worldwide, electric vehicle (EV) penetration goals have resulted in an average growth of 59% year over year, with 2.1 million light vehicle EV sales in 2018 (McKinsey 2019). Reaching ambitious EV goals will require significantly more charging stations for residents and drivers, including at workplaces, homes, apartments, and public fast charging stations. With charging infrastructure build-out directly linked with EV uptake, smart EV charging infrastructure planning is an emerging commercial building and community energy planning promising practice. To understand the emerging scope and speed of deployment of the needed EV charging infrastructure, the following provides an investigation into the City of Denver's goals, which are illustrative of many cities action plans in the United States (C40 2020). In the Denver mayor's Climate Action Plan, Denver set the goal of reducing greenhouse gas emissions 80% by 2050 (Denver Climate Action Plan 2018). The transportation sector is the second largest source of greenhouse gas emissions in Denver, and the Climate Action Plan identifies EVs as a key way to reduce greenhouse gas emissions from vehicles. To achieve these goals, Denver set a goal that by 2030, 30% of vehicles would be electric, growing to 100% of vehicles in 2050. Specific observations include (Denver Climate Action Plan 2018):

- Denver will require significantly more public charging stations—approximately 10,000 by 2030 and 25,000 by 2050
- Denver only has 350 public charging stations as of 2019
- Between 2017 and 2018, EV sales in Colorado increased by 70% (up to 5.36% of sales)
- New buildings will need to be equipped to charge EVs to help increase EV adoption
- Specific focus is needed on residential properties, in particular multifamily properties where more than 40% of Denver residents live and where there is greatest opportunity for recharging vehicles during idle time.

There are many factors involved in electrifying a fleet of vehicles and/or providing workplace or residential EV charging. Adequate planning requires a deep knowledge of vehicle routes, locations where charging will take place, available electrical distribution infrastructure, existing facility electricity usage, utility rates, insurance, federal and state policies, and vehicle costs. Key design and building infrastructure strategies to consider during building planning and design to enable these EV goals include:

- Determining the types of charging infrastructure currently available and to be provided
- Assessing and modeling how new EV loads impact zero energy goals as well as energy accounting, building peak demand, building electrical infrastructure, utility costs, and adaptive management opportunities
- Considering locations for EV charging stations based on alignment with distributed renewables and local building and utility electrical infrastructure constraints (and availability)
- Aligning with local proposed new construction codes by building type, with an eye to requiring charging infrastructure in new construction
- Enabling the future use of EVs as distributed energy resources for energy shifting and adaptive load management, including enabling future control and communications capabilities to minimize peak demand and maximize grid coordination opportunities.

Available Charging Infrastructure

A building development and design process takes time, so it is important to ensure adaptability in planning. This is particularly important in determining EV charging infrastructure needs, which are evolving rapidly. A building owner may deploy multiple kinds of EV charging systems based on the building type and occupant needs and connection to the energy system. The plan should determine how many charges are needed (including total number as well as single versus multiple vehicle chargers), where they should be located, and the type of charger required (e.g., Level 1, Level 2, or fast). Understanding the existing definitions of EVs and charging infrastructure is the first step in this process. The Southwest Energy Efficiency Project definitions include (SWEEP 2020a):

- **Battery electric vehicle (BEV) or plug-in hybrid electric vehicle (PHEV)**. A motorized vehicle registered for on-road use, powered by an electric motor that draws current from rechargeable storage that is charged by being plugged into an electrical source.

- **Electric vehicle supply equipment (EVSE)**. The electrical conductors and equipment external to the EV that provide a connection between an EV and a power source to provide charging, with varying levels of power delivery available (i.e., a charging station).
- **Level 1 EVSE**. Level 1 charging is provided by a standard electrical outlet and can be convenient for home use or extended parking sessions; it charges slowly, however, offering about 5 miles of range per hour and a power output less than 1.5 kW at 120 volts.
- **Level 2 EVSE**. Some home chargers and most public charging stations are Level 2, which can add 12 to 25 miles of range per hour, depending on the type of EV and its onboard charger at 3 kW to 7 kW at 208/240 volts; Level 2 EVSEs are ideal for times when the vehicle will be parked for at least an hour, such as at work, restaurants, movie theaters, sporting events, or longer shopping trips.
- **EV fast charger**. EV supply equipment with a minimum power output of 20 kW, often referred to as a DC fast charger; this device enables a quicker charge and is typically located in public areas with access for long distance trips (note that not all EVs have DC fast charge capabilities).
- **EV load management system**. A system designed to allocate charging capacity among multiple EVSEs.
- **EV-capable space**. A designated parking space with conduit sized for a 40-amp, 208/240-volt dedicated branch circuit from a building electrical service panel to the parking space and sufficient physical space in the same building electrical service panel to accommodate a 40-amp dual-pole circuit breaker.
- **EV-ready space**. A parking space that is provided with one 40-amp, 208/240-volt dedicated branch circuit for EV supply equipment that is terminated at a receptacle, junction box, or Level 2 EVSE within the parking space
- **EVSE installed space**. A parking space with EVSE capable of supplying Level 2 with current at 40 amps at 208/240 V.

Based on the possible locations for EV charging infrastructure, building designers can consider the following deployment scenarios to maximize alignment of this new electrical load with renewables and reduce infrastructure and peak demand costs:

- **Charging at work in office buildings**. Daytime loads with Level 2 EVSEs align well with the lowest-cost renewables. Utility demand charges can be mitigated with smart charging controls.
- **Charging at single-family homes**. Lower-power Level 1 EVSEs and overnight charging reduces overall peak loads and can be aligned with off-peak periods for time-of-use rates to minimize charging costs.
- **Charging in apartment and multifamily buildings**. Lower-power Level 1 EVSEs and overnight charging reduces overall peak loads and can be aligned with off-peak periods for time-of-use rates to minimize charging costs.
- **Strategic destination charging** (hotels, park-and-rides, gyms, schools, etc.). Provides charging infrastructure anywhere vehicles are parked for extended periods of time.

- **Fast charging** (long distance travel and fleets). Additional charging flexibility and demand management is possible with demand-management controls on EV charging infrastructure.

New Construction Codes for Charging Infrastructure

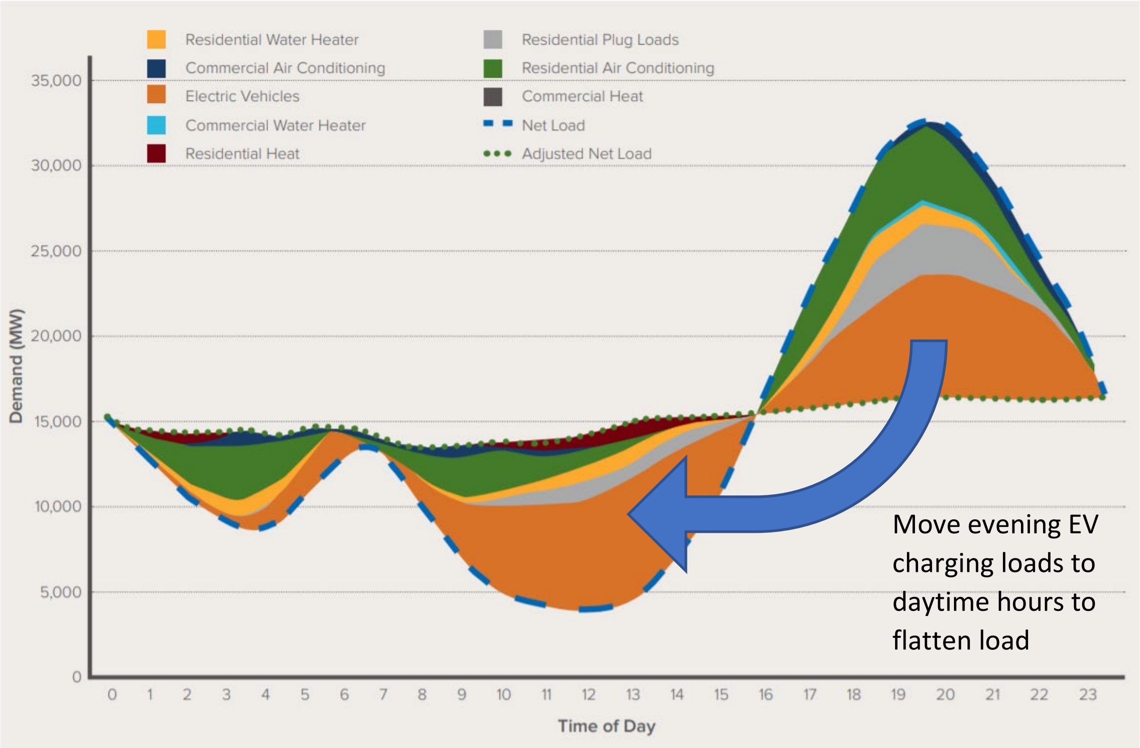
According to the Southwest Energy Efficiency Project (SWEEP 2020b), approximately half of all vehicles in the United States belong to residents of single-family or duplex homes with access to a dedicated off-street parking space, such as a garage or driveway that could be used for overnight EV charging. The other half do not have reliable access to a dedicated off-street parking space at an owned residence, so there is a need to expand charging access to multifamily unit dwellings, workplaces, and commercial properties. In addition, the installation of an EV charging station is 64%–75% less expensive when the infrastructure is installed during initial construction rather than retrofitted in existing buildings (Pike et al. 2016). Therefore, new construction codes for EVSE charging infrastructure are being developed to ensure these EV charging capabilities become available as buildings and communities are built out over time. For example, Table 1 indicates a local city jurisdiction's 2019 proposed new construction code requirements for charging stations to be installed by building type (Denver Community Planning and Development 2019).

Table 1. Electric vehicle infrastructure Denver proposed code requirements (proposed in 2019)

	Number of EV-ready spaces	Number of EV-capable spaces	Number of EVSE installed spaces
Single-family homes and townhomes			
Parking space in a garage	1 in every parking garage	None	None
Multifamily EV infrastructure			
1 space	1	None	None
2–9 spaces	1	20% of space	None
10 or more spaces	15% of spaces	Remainder of spaces	5% of spaces
Commercial and parking garage EV charging infrastructure			
1 space	1	None	None
2–9 spaces	1	1	None
10 or more spaces	10% of spaces	10% of spaces	5% of spaces

Aligning EV Charging with Distributed Renewables

In a recent Rocky Mountain Institute evaluation of the future of buildings, EV charging, and the grid, researchers identified key strategies for building systems and loads that could enable more cost-effective grid integration and the addition of renewables to the grid (Goldberg et al. 2018). The authors modeled the use of demand flexibility strategies to shift electricity consumption from times of the day with high demand but low renewable supply to times with high renewable supply. As shown in Figure 1, the authors identified EV charging loads as the largest opportunity utility system-wide to maximize the benefits of demand flexibility, suggesting that developing a grid-coordinated EV charging infrastructure could be a key strategy to reduce utility system costs and maximize alignment of loads with renewable generation.



Move evening EV charging loads to daytime hours to flatten load

Figure 1. Opportunity for flexible EV loads to reduce utility system peaks and flatten loads (Goldberg et al. 2018)

Building Energy Models and EV Charging Loads

The U.S. Department of Energy (DOE) Zero Energy Building and Campuses Common Definition, as well as the U.S. Green Building Council's LEED Zero Building certification program, provide specific guidance for how to treat EV charging loads in the zero energy building accounting (DOE 2015):

Zero Energy Building (ZEB) energy accounting would include energy used for heating, cooling, ventilation, domestic hot water (DHW), indoor and outdoor lighting, plug loads, process energy, and transportation within the building. Vehicle charging energy for transportation inside the building would be included in the energy accounting. On-site renewable energy may be exported through transmission means other than the electricity grid ***such as charging of electric vehicles used outside the building****.*

For a building or district that provides electricity to charge EVs used for transportation to and from the district, this load, if separately metered, is considered an export option rather than an additional load to offset with renewable energy. However, the interaction with the local electrical distribution system as well as the impacts on building's peak demand or time-of-use rate costs also need to be considered. As such, there is increasing interest in grid-interactive efficient buildings and the role that building demand flexibility can play in providing value to building owners while also providing benefits to the grid, such as enhanced resilience, deferring capital expenditures, and supporting the balance of renewable energy generation supply (DOE 2020). As previously identified, a major potential future source of demand flexibility in buildings and communities is EV charging. As a first step, it is critical to understand the potential impact that uncontrolled EV charging can have on the typical load profiles of buildings and communities. With that knowledge, EV charging can be controlled and optimized, along with other building demand flexibility technologies, to manage building-scale and community-scale loads to achieve targeted benefits. Physics-based, predictive modeling helps facilitate the estimation of EV charging impacts and the optimization of EV charging controls from a whole-building or whole-community integration perspective.

A Zero Energy District Modeling Example

The National Renewable Energy Laboratory (NREL) partnered with Panasonic on the design of the Peña Station NEXT (PSN) development. PSN will occupy a 400-acre site, where 103 buildings are planned. The development is anchored by a Panasonic office. The planned development includes residential, hotel, office, and retail buildings. The goal of the development is to be net zero energy, with much greater than 50% penetration of distributed energy resources (Doubleday et al. 2019). NREL led the analysis that will support the design of energy systems for PSN in the context of the net zero energy goal. As part of the project, NREL assessed the expected impact of EV loads on PSN's overall electric load profile and the local distribution grid. NREL constructed energy models of the 103 planned buildings at PSN, with the integration of EV charging loads, using URBANopt and OpenStudio®. URBANopt is a district- and community-scale modeling platform originally developed by NREL and now being developed as a collaborative, open-source project. According to its developers, "the URBANopt platform uses the OpenStudio platform to perform detailed energy modeling at the individual building level using EnergyPlus" (Polly et al. 2016). OpenStudio is a "cross-platform collection of software tools to support whole building energy modeling using EnergyPlus," and is developed in collaboration by five national laboratories (NREL, Argonne National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory) (NREL 2020a).

Within URBANopt, OpenStudio models are configured programmatically through a workflow consisting of a series of Ruby scripts, known as "OpenStudio measures." OpenStudio measures modify components or values in an OpenStudio model. OpenStudio measures can be leveraged for many additions or modifications to OpenStudio models, including creating or altering model geometry, systems, or loads, and reporting of output values (NREL N.D.). NREL maintains the Building Component Library (BCL), which is a repository of model components and OpenStudio measures available for use by the public and is accessible online and in the OpenStudio application (NREL 2019). Because OpenStudio does not yet have the capability to access all components of the underlying EnergyPlus model structure, it is sometimes necessary to leverage "EnergyPlus measures," which are analogous to OpenStudio measures, but operate on the EnergyPlus model directly (NREL N.D.). In this work, an OpenStudio measure was written to add an EV charging load to a building energy model, and this measure was integrated into a workflow for URBANopt. Additionally, an EnergyPlus measure was written to control an EV charging load in a building energy model. The OpenStudio measure is available to be publicly used through the BCL.

Adding an EV Charging Load to a Building Energy Model

The OpenStudio measure is based on static profiles of power draw for EV charging. The profiles were created leveraging output from the EVI-Pro Tool, generated as part of a study of projected future EV adoption for the state of California (Bedir et al. 2018). These data are also accessible through the California Energy Commission EV Infrastructure Projection Tool (NREL 2018). The work of Bedir et al. leverages results from the 2010–2012 California Household Travel Survey. NREL developed the EVI-Pro Tool in collaboration with the California Energy Commission. According to the tool's developers (Wood et al. 2018), "The fundamental assumption in EVI-Pro is that consumers prefer charging infrastructure that enables them to complete all their travels (based on current vehicle use) while minimizing operating cost." The initial EV analysis focused on light-duty vehicles only. Future analysis could consider autonomous electric shuttle vehicles, an "electric roadway" for wireless charging of hotel and parking shuttle buses, and high-powered fast charging of mass transit vehicles and other fleets.

EVI-Pro analysis considers both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). EVI-Pro assumes that drivers of PHEVs seek to maximize the portion of their vehicle miles traveled that are powered by electricity (eVMT). The charging profiles are divided into residential, public, and workplace charging stations. Residential charging represents charging at homes or apartment buildings. Public charging represents EV charging at parking for retail stores or public buildings. Workplace charging represents charging by employees at a workplace. Residential and workplace charging stations were assumed to be Level 1 and Level 2. Public building charging stations were assumed to be DC fast chargers. Each of the 103 buildings modeled for the PSN site was assigned one of these types of charging stations.

Charging Profiles

The process for generating EV charging profiles is depicted in Figure 2, as well as an alternative process for generating inputs to the analysis based on the recently released EVI-Pro Lite web tool. Inputs that can be generated from the EVI Pro Lite web tool are shown in orange. In this study, separate EV charging profiles were developed for three different day types (weekdays, Saturdays, and Sundays) for each of the three locational charging types (residential, public, and workplace) at PSN. Building occupancy was used as a proxy for vehicle population. Building occupancy was determined based on occupancy schedules from OpenStudio Standards used in the building energy models. OpenStudio Standards aggregates information from building energy performance standards such as ASHRAE 90.1, as well as standardized modeling inputs from sources such as ASHRAE 90.1 Appendix G, for use in OpenStudio energy models, and generation of code-compliant baseline models (NREL 2020b).

The EV charging profiles generated for Peña Station assumed that 50% of the light-duty vehicles on the site were plug-in EVs, which is about 10,000 plug-in EVs throughout a typical weekday. The profiles assume that PSN residents use residential charging, but not workplace or public charging, and that commuters to the site use workplace or public charging, but not residential charging. A series of EV charging events on a given day type were generated using the EVI-Pro model with travel data from California, and off-site charging events were then discarded. EVI-Pro Lite is a simplified version of EVI-Pro and is available publicly online. EVI-Pro Lite allows users to estimate the number and type of charging stations required to support a given number of EVs in a metropolitan area or state. The data supporting EVI-Pro and EVI-Pro Lite enable extensibility of this analysis (NREL 2020c).

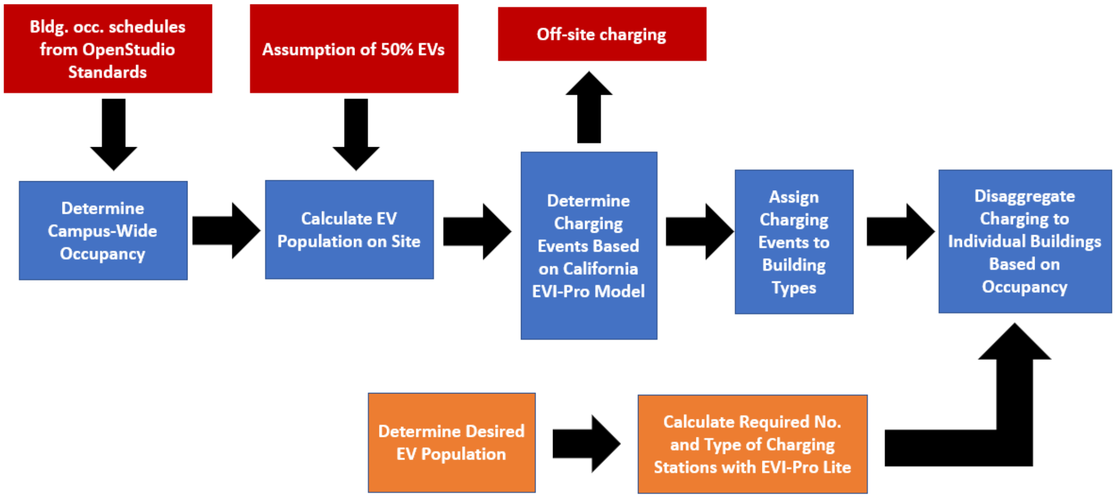


Figure 2. Flow chart depicting process of generating EV charging profiles

Charging events were assigned to categories of building types (public, workplace, and residential), and disaggregated to the individual building level based on building occupancy. EV charging profiles from EVI-Pro reflect a given population of EVs of each of several battery capacities. The EV charging profiles for PSN reflect the disaggregation by battery capacity shown in Table 2. In the abbreviations, the numeric suffix indicates the electric range, in miles.

Table 2. Disaggregation of plug-in electric vehicles at PSN by type

Vehicle type	Fraction of EVs at PSN
PHEV20	15%
PHEV50	35%
BEV100	15%
BEV250	35%

EV charging profiles were developed for three different scenarios for charging behavior, and three different scenarios for charging flexibility. The charging behavior scenarios are as follows:

- “Business as usual” home dominant charging behavior: The majority of the electrical energy consumed by EV charging is attributable to charging of EVs at home during the evening hours and overnight.
- Free workplace charging at PSN: The peak power draw from EV charging on weekdays occurs during morning hours, due to EV charging at workplaces. Overnight residential EV charging remains a significant share of the total electricity use for EV charging.
- Free workplace charging across the Denver metro area: Home EV charging is reduced relative to the “free workplace charging at PSN” scenario, because residents of PSN who work elsewhere can charge their vehicles for free at those workplaces.

Plots of the EV charging load on a weekday under each of these scenarios are shown in Figure 3. The plots show disaggregation by home charging (Level 1 and Level 2), workplace and public charging (Level 1 and Level 2), and DC fast charging. The charging flexibility scenarios apply to workplace charging only, and are as follows:

- Minimum delay: EVs begin charging immediately upon arriving at work
- Maximum delay: EVs are plugged in immediately but do not begin charging until necessary
- Minimum power: EVs are charged at minimum rate over the parking event.

Across the three charging flexibility scenarios, the same amount of energy is delivered per charging session. The "minimum power at work" scenario reduces the overall peak EV charging load, and the "maximum delay at work" scenario shifts the peak EV charging load to later in the day. Plots of the EV charging load on a weekday under the "free workplace charging at PSN" scenario, and each of the three charging flexibility scenarios, are shown in Figure 3. The vehicle load scenarios considered could be applicable to other campuses and developments.

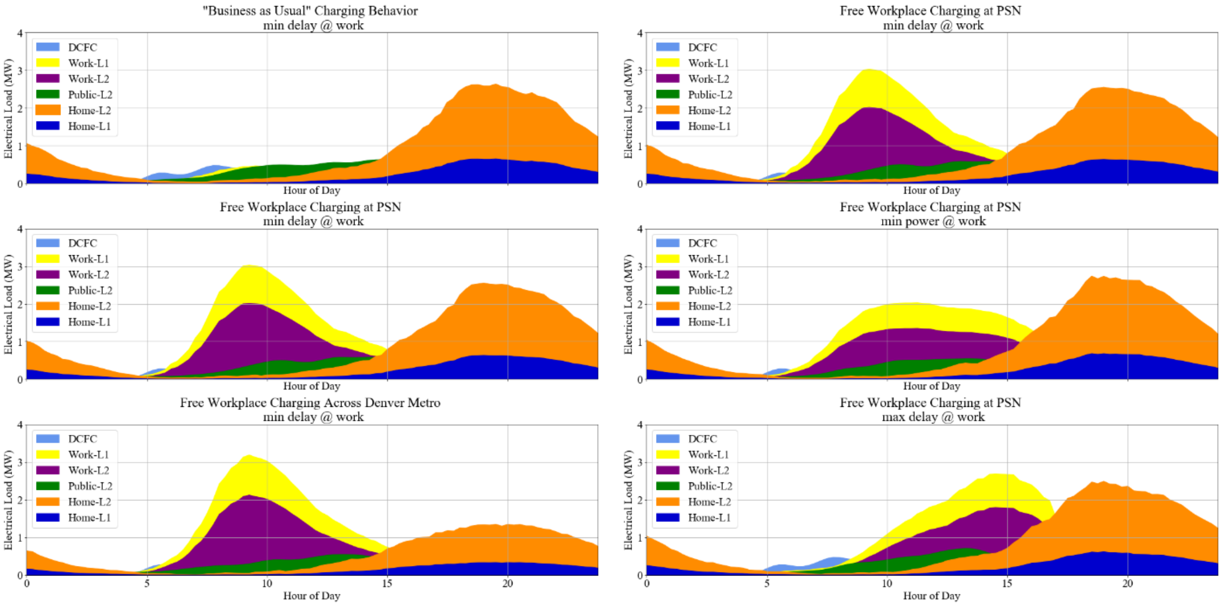


Figure 3. EV charging load under three charging behavior scenarios and three charging flexibility scenarios

OpenStudio Measure

As configured for the PSN analysis, the OpenStudio measure selects an EV charging power draw profile for a given building and set of conditions (charging behavior and control) and adds the EV charging to the building electrical load. For future analysis (beyond the PSN project), the measure allows the user to linearly scale the level of EV penetration for a generalized profile for the building type (work, retail, or home), which is an average of the profiles generated for those building types at PSN. This scaling factor could be used to reflect building occupancy levels differing from those assumed in the prototype buildings. The user selects a charging flexibility option, a charging behavior option, a building type, and a penetration level of EVs (as a percentage) of light-duty vehicles associated with the building to configure the measure. The charging flexibility and behavior options are described previously.

Controlling EV Charging in a Building Energy Model

The EnergyPlus EV charging control measure was written with a workplace charging application in mind and allows the user to control charging to better align it with expected solar photovoltaic (PV) power generation. This sort of control could be leveraged for demand response purposes. The measure uses the EnergyPlus Energy Management System feature and uses site-specific solar irradiance as a proxy for PV power generation. The measure ensures that vehicles are fully charged by the end of the workday. The measure was written as a demonstration for a scenario in which EV charging loads are known a priori, with the “baseline” (uncontrolled) EV charging load taken as an input.

For illustrative purposes, the EV charging control measure was applied to the prototype office building model available from DOE, with a modified version of the average EV charging loads from PSN added to it. DOE publishes “prototype” building models in OpenStudio format for a variety of building programs, which are intended to represent typical buildings in the United States, and are supported by extensive documentation (DOE 2018). The prototype office building model is configured with an occupied schedule of 7 a.m. to 6 p.m. on weekdays. The EV charging loads were scaled by a factor of 10 from the PSN load profiles to make the EV load a more significant fraction of the overall building load. Note that this prototype building has the same occupancy patterns assigned as in the prototype buildings used to generate the occupancy data for the PSN project that underly the EV charging loads embedded in the measure. Figure 4 shows the effects of load-shifting on the building’s overall load profile and on the EV load profile during a cloudy day in May. The EV charging load is reduced during the hours of 8 a.m. to 3 p.m., and is increased from 3:30 p.m. to 6 p.m., better aligning its consumption with solar irradiance, and thus, solar PV power generation.

The measure implements the following sequence of operations on weekdays, with

$$P_{EV\_Sched} = Scheduled\ power\ draw\ of\ EV\ charging$$

$$P_{EV} = Actual\ power\ draw\ of\ EV\ charging$$

$$Sig_{DR} = \text{Demand response signal, between 0 and 1}$$

- If time is between 8 a.m. and 3 p.m.:
    - If solar irradiance is below 100 W/m^2, set demand response signal to 1.0.
    - If solar irradiance is between 100 W/m^2 and 250 W/m^2, set Sig_{DR} proportionately between 1 and 0.
- Based on the demand response signal:

  Set $P_{EV} = (1 - Sig_{DR}) * 0.75 * P_{EV,Sched}$,

  constrained by a minimum value of 100W for P_{EV}, based on the minimum turn-down capabilities of EV chargers.

- If the time is 3 p.m.:

- Reset Sig_{DR} to 0. Increase the EV charging load proportionately to the amount of energy curtailed, and the remaining hours until 6 p.m., to ensure that all vehicles are fully charged by 6 p.m.

The EV charging load present at PSN office buildings on weekends is minimal, and thus no control of EV charging load is performed on weekends.

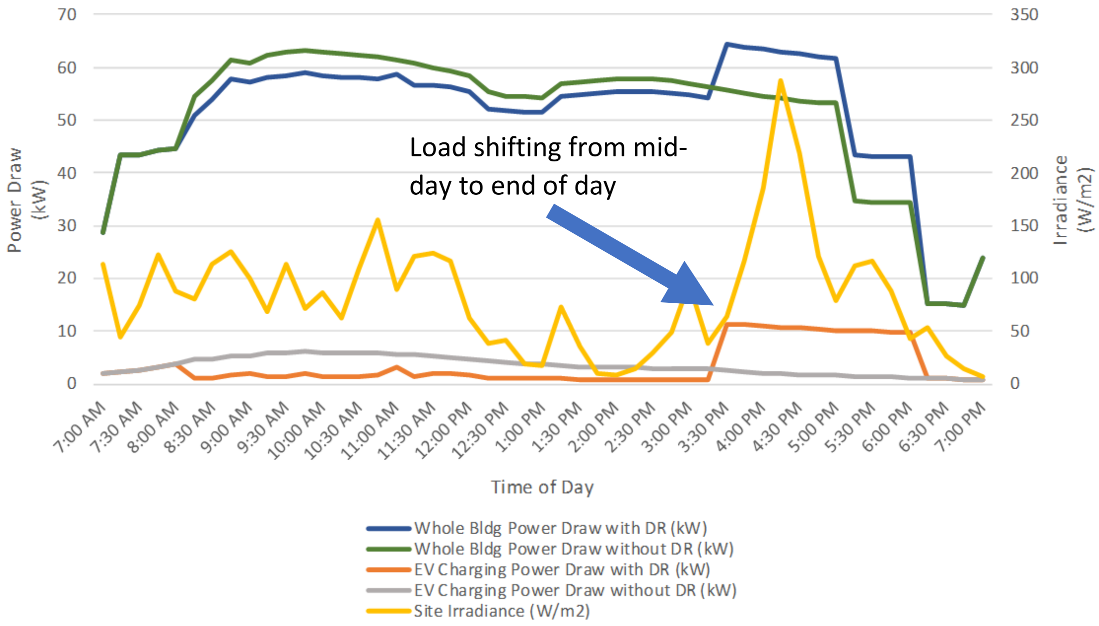


Figure 4. Effects of load shifting on EV charging profile and whole-building load profile

For more general analysis for EVSE infrastructure planning in districts, this workflow allows energy planners to scale the level of EV user penetration for a generalized profile for the building type (work, retail, or home) across common demand management control strategies. This workflow, when integrated with the building energy modeling analysis for the district, enables EV infrastructure planning to be included in the full district energy analysis and feasibility studies.

Managed Charging at the Workplace—A Case Study

NREL's living laboratory infrastructure enables its campuses to be utilized as a research instrument to study integration of renewable energy and energy efficiency and address a range of its own operational needs. The parking facilities are no exception. In addition to fulfilling their primary function, the parking facilities at NREL's South Table Mountain and Flatiron campuses provide the opportunity for NREL researchers and its partners to test the impact of various plug-in EV charging scenarios on the electrical distribution network, to test vehicle-to-building energy control integration, and to gain understanding of charging behaviors for valuing and developing charge scheduling programs, all of interest to utilities, businesses, and agencies. In 2018, NREL partnered with PowerFlex Systems to evaluate the adaptive charging capabilities for a 50-kW DC fast charger integrated with 16 L2 demand-managed workplace charging stations. The adaptive charging approach was combined with building load and demand profile inputs to enable building demand charge mitigation and electrical infrastructure cost reductions due to managed EV-to-building integration. As documented recently by Bernal et al. (2020), the adaptive charging strategy for this initial deployment reduced the cost of the building's electrical equipment by 48% and 42% for DCFC plus L2s and only L2s, respectively. In addition, building peak demand savings were documented, with varied savings ranges based on research constraints and magnitude of EV loads versus building loads.

More recently, NREL adapted these research activities into its Golden, Colorado, main campus site operations by implementing a large-scale workplace charging system with load control strategies, utilizing the adaptive charging system to engage more than 250 daily EV commuters. All 124 of NREL's 6.6-kW Level 2 EV charging stations available to staff and visitors for recharging personal EVs are networked and "smart." The Adaptive Charging Network (ACN) system operates the EVSEs, providing NREL the ability to control access, collect payment, and manage electrical load as part of an intelligent campus energy strategy. A team of both researchers and operations staff manages the system, determining how to balance the load to mitigate peak demand fees for electricity and optimize campus energy consumption.

The layout for the EVSEs supports the design of ACN load management and control system and minimizes NREL's electrical infrastructure costs by approximately 50%. This design required less electrical infrastructure, allowing for automatic sharing of the limited transformer capacity powering the EVSEs to be rated below the peak rating of the EVSEs (to as low as 3.3 kW/EVSE in some locations). Figure 5 shows the scenarios that feature load management technology where labor and material savings were realized due to the smaller sizing of equipment, wiring ratings, and reduced installation time. Key capital costs savings included downsizing from a 150-kVA to a 75-kVa transformer, and utilizing existing space in the building main distribution panel (which enables not needing a building-wide electrical shutdown or upgrading the building electrical service and minimizing the distance of the electrical runs).

In addition to the transformer limitations, the EVSEs are managed to reduce total campus load during peak demand events on campus. The ACN system collects user inputs through use of an app at the initiation of each charge session. These inputs, including the number of miles of energy requested and the estimated time of departure, are aggregated and integrated within the load management control system to optimize delivery of the requested energy using real-time campus load data and the total energy requests from the EVSEs.

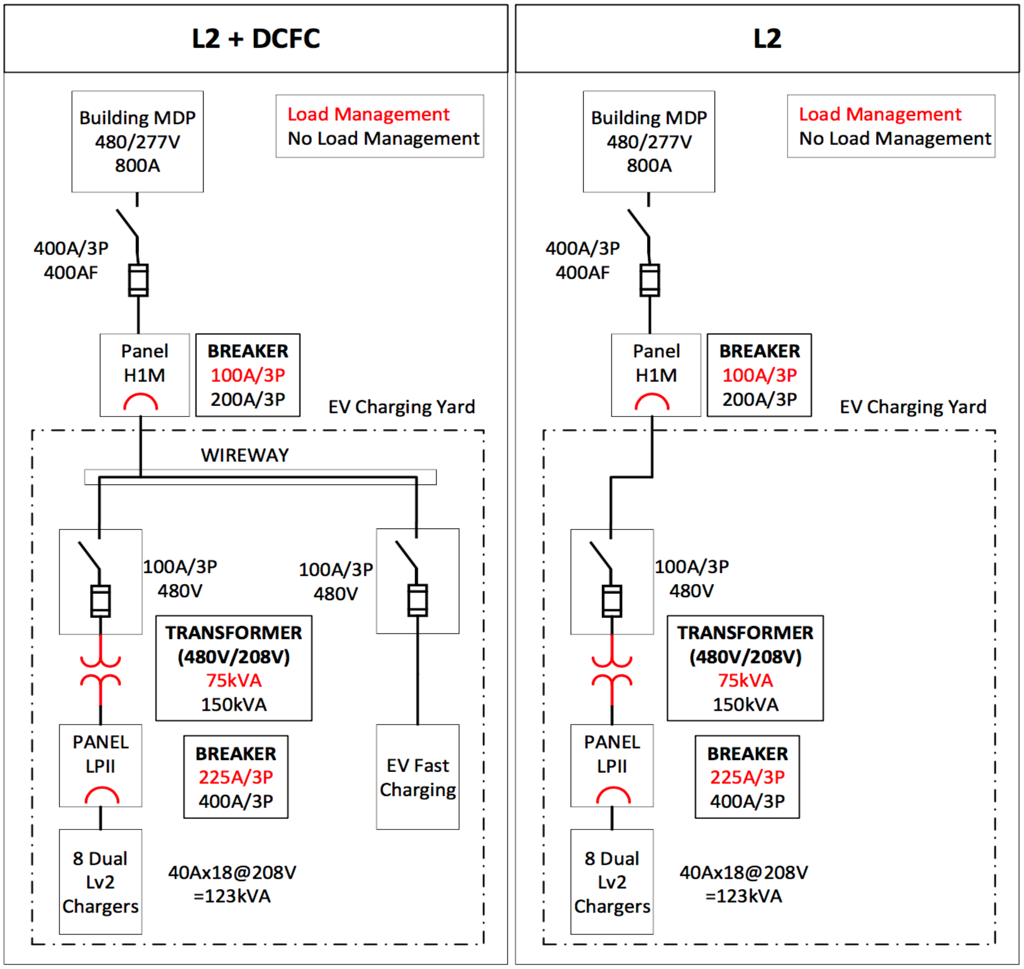
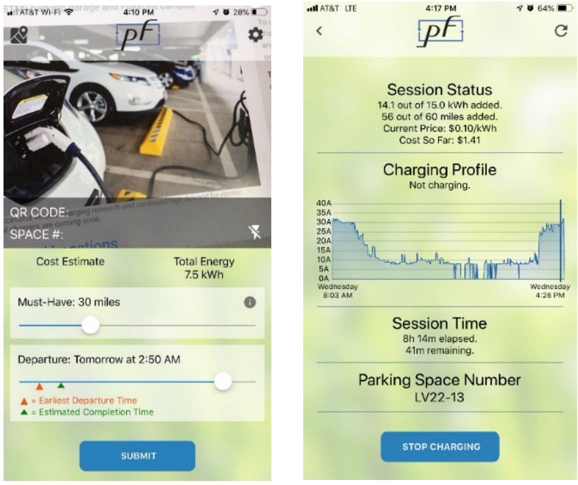


Figure 5. Electrical infrastructure sizing example with and without load management for a DC fast charger and a bay of Level 2 charging stations. *Source:* Bernal et al. 2020

NREL is required to recover costs for the electricity and annual operations and maintenance of the stations from users based on federal guidance contained in the Fixing America's Surface Transportation Act. The ACN user app enables the communication between the driver, the EVSE, and the load management control system to meet this requirement, as shown in Figure 6. Users pay a per-kilowatt hour rate for their charge session. NREL created a variable pricing structure that aims to incentivize user behavior by setting rates for each kilowatt hour depending on the amount of flexibility the charge request provides to NREL. Higher rates are assigned for less flexible requests. The variable pricing structure allows NREL to more equitably manage the range of EV charging requests based on the potential risk the request presents to NREL of exceeding the capacity of the transformers and of incurring demand charges from the load of the EVSEs during peak campus demand events.



Cost Estimate

Total Energy
7.5 kWh

Must-Have: 30 miles

Departure: Tomorrow at 2:50 AM

▲ = Earliest Departure Time
▲ = Estimated Completion Time

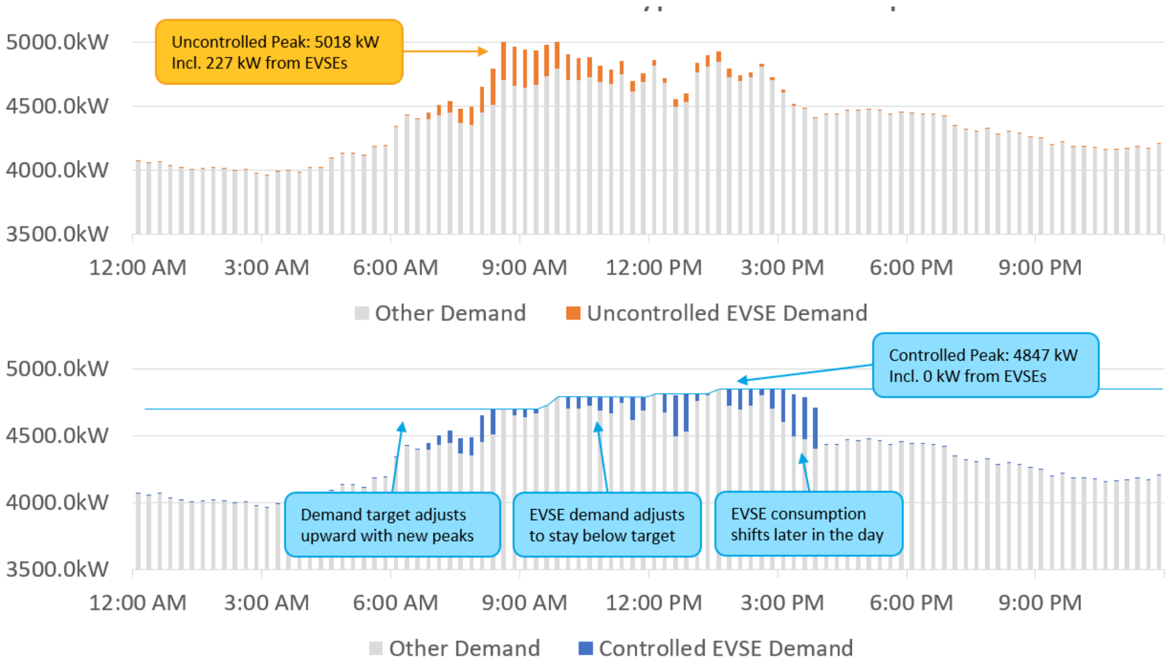
Session Status
14.1 out of 15.0 kWh added.
56 out of 60 miles added.
Current Price: $0.10/kWh
Cost So Far: $1.41

Charging Profile
Not charging.

Session Time
8h 14m elapsed.
41m remaining.

Parking Space Number
LV22-13

Figure 6. User input example for workplace charging management



Uncontrolled Peak: 5018 kW
Incl. 227 kW from EVSEs

Controlled Peak: 4847 kW
Incl. 0 kW from EVSEs

Demand target adjusts upward with new peaks

EVSE demand adjusts to stay below target

EVSE consumption shifts later in the day

Figure 7. Workplace-managed charging peak demand savings

Figure 7 demonstrates an example day of how this load flexibility across 100+ L2 workplace charging stations can be redistributed to off-peak time windows and aligned with available PV generation. Using the NREL pricing structure, the ACN user app estimates total costs for the charge session. The ACN system then controls the EVSE and delivers the requested energy within the user requested timeframe and charges the user for that session once completed.

Potential Future Work and Conclusions

The EV charging control approach could be refined in future work. The control logic could be configured to seek to control the EV charging load based on a deterministic schedule, or to achieve a desired "net load" profile for the building, where the net load is the difference between the building's total load and on-site power generation. The approach could be modified for cases in which the EV charging load is not already known, though this would introduce uncertainty around whether all vehicles would be fully charged by the end of the workday. The modeling approach could also be extended to generate EV charging load profiles based on user inputs and building-specific parameters, instead of using static profiles generated based on higher-level characteristics, leveraging EVI-Pro or other sources.

Across the United States, there is a growing demand for EV charging infrastructure, especially in office, retail, and multifamily buildings, and building designers are now being asked to consider the electrical infrastructure, peak demand implications, and the greater grid integration and control options. In this paper, we documented methods to design and understand peak demand and grid coordination EV charging control strategies by developing energy modeling approaches that enable the design optimization and building impacts of uncontrolled and demand-managed charge control approaches. In addition, a full-scale example of an ACN is presented, including the design approach, control approach, and user interface for a workplace-managed charging solution. The case study presented demonstrates the opportunity to minimize office building peak demands and maximize self-consumption of a variable PV resource.

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