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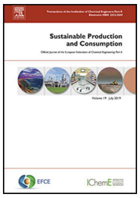

# Operational grid and environmental impacts for a V2G-enabled electric school bus fleet using DC fast chargers

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ABSTRACT

As states replace diesel school buses with electric ones, utilities will want to control charging schedules to capture potential benefits on the grid and avoid all buses charging at the same time, adding a large electric load. Vehicle-to-grid (V2G) services can provide more grid stability and reduced carbon dioxide emissions than simple controlled charging systems, yet the grid impacts of V2G school buses have not been modeled using realistic school bus schedules. This paper develops a methodology for simulating the effect of managed charging of electric school buses on peak shaving in the state of North Carolina using V2G interactions and DC fast chargers to determine potential emissions reductions by minimizing peak load periods. The V2G-Sim model is used to manage fleet-wide charging, while minimizing peak generation of electricity on the grid and flattening the load curve under different battery capacities, charger power ratings, and fleet sizes. Historic annual peak hours are examined to determine the feasibility of reducing generation capacity, and the daily peak hours are examined to determine the potential peak shaving and subsequent avoided emissions. The results demonstrate that at full electric school bus replacement, 14,000 V2G buses can aggregate and shift 2.6 GWh in North Carolina, avoiding up to 1,130 t of carbon dioxide emissions per day, assuming decreased dependence on natural gas peaker plants. An additional 1,500 t of $CO_2$ can be avoided by replacing diesel-powered buses compared to the 320,000 t total daily $CO_2$ emissions from all activities in North Carolina. Additional emissions are avoided by the replacement of diesel buses with electric buses. The largest greenhouse gas emission benefit is the replacement of diesel with electric school buses, and the ability to shave peak loads is maximized on weekend days in the winter. The model can be used by researchers, the utility, and states as these entities evaluate the environmental and operational grid benefits of a V2G school bus program.

## 1. Introduction

The electric vehicle (EV) market is growing in the United States, as costs decrease and vehicle driving ranges increase. Utilities are investigating controlled charging as a means to mitigate the impacts EV growth will have on electricity demand (Steward, 2017). Controlled charging can come in the form of unidirectional vehicle-to-grid (V1G) charging or bidirectional (V2G) charging and discharging. V2G allows vehicle batteries to act as storage of excess renewable energy or low-cost fossil fuel energy that can be dispatched as necessary to offset steep ramps or high peaks in the load (Steward, 2017). This form of managed and controlled smart charging can reduce the volatility of unidirectional charging and may provide benefits to the grid operators in the form of cost savings, reduced greenhouse gas emission reductions, or operational efficiency. However, the extent to which V2G benefits match with existing vehicle schedules and overall school bus fleet behavior remains a gap in study and implementation.

Public school bus fleets represent strong candidates for pilot V2G programs due to their limited route distances and predictable travel schedules compared to other fleets or consumer vehicle patterns. School buses are often stationary at key hours for grid stabilization, namely midday and early evening peaks, which match with electric grid demand. Additionally, the fact that a single school district owns and operates dozens of buses means that the process of electrifying the entire school bus fleet poses fewer obstacles than electrifying all consumer vehicles in the state managed across multiple jurisdictions.

Several states have already begun to purchase electric school buses with funds allocated for various clean energy projects. Massachusetts developed an electric school bus pilot program to de-

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**Nomenclature**

| | |
|---|---|
| t | time |
| i | vehicle |
| netload | electrical load ± the (dis)charging load |
| $P_{max}$ | maximum charging power for vehicle i |
| $SOC_{max}$ | maximum state of charge for vehicle i |
| $SOC_{init}$ | initial state of charge for vehicle i |
| $C_i^t$ | battery consumption of vehicle i at time t |
| $EF_{peak}$ | emission factor of fuel used during peak |
| $L_{orig}$ | original electrical load |
| $T_{peak,i}$ | time at which peak shaving begins |
| $EF_{diesel}$ | emission factor of a diesel bus |
| T | number of time intervals in model |
| V | number of vehicles in model |
| $P_{charge,i}$ | the power (dis)charged for vehicle i |
| $P_{min}$ | maximum discharging power for vehicle i |
| $SOC_{min}$ | minimum state of charge for vehicle i |
| $SOC_{final}$ | final state of charge for vehicle i |
| $E_i$ | battery capacity of vehicle i |
| $E_{red}$ | daily reduced emissions |
| $L_{opt}$ | optimized electrical load |
| $T_{peak,f}$ | time at which peak shaving ends |
| $FE_{diesel}$ | fuel economy of a diesel bus |

ploy and track three buses (Sears et al., 2018). The program was designed to test reliability and costs over a one year period. While the program did not test V2G bidirectional charging services, it concluded that revenue from V2G would be necessary to reach a break-even point prior to the end of the bus's useful life (Sears et al., 2018). The corresponding report also notes that a partnership with the utility is essential to a successful V2G program. Previous studies have focused on the economic feasibility of electric school buses as this has been the primary barrier to integrating them into fleets. Yet, without managed and bidirectional charging components, economic barriers have been high thus far. Noel and McCormack conclude that electric buses cannot be cost-effective without V2G services and without considering the health benefits (Noel and McCormack, 2014).

Seeking to overcome these previous economic challenges in electric bus deployment and improve infrastructure capability in the U.S., the Biden administration has set a goal that "all new American-built buses be zero-emissions by 2030", a goal that will be accelerated "by converting all 500,000 [U.S.] school buses... to zero emissions" (Biden, 2020). The plan does not explicitly refer to electric-powered zero-emission school buses, leaving room for alternative low-carbon vehicle technologies. Hydrogen fuel cells may be another option for buses since hydrogen is considered a zero-emission fuel although the majority of upstream hydrogen production is converted from natural gas (U.S. Department of Energy 2020). Given that electric bus manufacturers are already established in the U.S., and electricity is pervasive, hydrogen buses may be an unlikely choice without significant added infrastructure investment. Therefore, electric buses may be grid-ready, and this study assesses the charging profile compatibility with typical school schedules. Additional motivations for this study are outlined in the sections that follow.

### 1.1. Health Benefits

There are major health benefits to switching from diesel-powered vehicles to electric school buses in terms of mobile sources of air pollution. Public school buses often operate with diesel fuel, which produces high amounts of particulate matter and greenhouse gas emissions. Particulate concentrations have been found to be 5–15 times higher inside of school buses than concentrations surrounding the vehicle (Wargo et al., 2002). These fumes such as NOx, SOx, VOC and CO increase the risk of asthma, cancer, cardiovascular issues, and developmental harm to the students and drivers (U.S. Environmental Protection Agency 2009). Electric buses do not emit particulate matter from the exhaust into the vehicle and are therefore safer for the passengers and those in proximity of the school (Wargo et al., 2002). For children undergoing early adult development, it is best to avoid particulate matter exposure to minimize unintended long-term debilitating effects of exposure to harmful diesel pollution. Recent studies have linked asthma, exacerbated cardiopulmonary effects, heart disease, and stroke to early life chronic exposure to diesel fumes and combustion.

### 1.2. Greenhouse Gas Emissions

With increased attention on reducing greenhouse gas emissions to deal with climate change, cross-sectoral approaches such as electrifying transportation have been identified as "win-win" opportunities to utilize higher shares of electricity in the energy sector, where renewable and low-carbon electricity options provide low-cost power supply. The carbon intensity of transportation has not decreased in the US as rapidly as electric power, and therefore opportunities that could be mutually beneficial for energy and transportation are needed. Additionally, greenhouse gas emissions from the transportation sector are reduced as the penetration of EVs increases due to the replacement of internal combustion engines in school buses. Replacing diesel with electric buses offsets even more emissions than the replacement of gasoline-powered vehicles because diesel combustion emits 13% more $CO_2$ than gasoline combustion (The International Council on Clean Transportation 2019). It is important to note, however, that some of these emissions are merely transferred to the electricity sector if the vehicles charge with electricity generated from fossil fuels. For this reason, clean electricity generation and storage solutions are needed to fully mitigate greenhouse gas emissions from both the transportation and electricity sector as a net-zero emission strategy (Kittner et al., 2021).

Emissions from the electricity sector come from the combustion of fossil fuels which is highest during peak demand hours from the most polluting power plants that operate on the margin (N.C. Sustainable Energy Association 2015). Natural gas peaker plants and coal plants are utilized to meet demands above the base load due to their flexibility and low costs. To reduce electricity emissions, batteries can be charged with low-carbon resources such as nuclear or solar and discharged strategically to shave peaks and mitigate ramps in the load (Arbabzadeh et al., 2019).

### 1.3. Grid Optimization and Stability

North Carolina ranks second in the nation in installed solar generation capacity and is continually adding more capacity (U.S. Energy Information Administration 2019). Solar power is intermittent and therefore requires other, flexible generation such as storage to maintain stability. Electric school buses have large batteries that are stationary most of the day during the school year and all day during the weekend and summer months, and therefore can potentially stabilize solar if their contribution can scale.

V2G turns electric vehicles into dispatchable storage assets for the electric grid offering optimization of the load because batteries can be used to redistribute the load from the peak (peak shaving) to the trough. When the total load is flattened, less power generation capacity is needed to meet the demand.

It will be important for school bus operators and planners to understand the potential benefits of a transition to electric school buses, and test the hypothesis of whether the benefits of managed and controlled electric school bus charging outweigh uncontrolled bus charging. It is also helpful for grid operators to understand how electric school bus deployments will affect overall system-wide load profiles and peak coincident demand for electricity. This study is the first study to simulate a total school buses fleet's typical operating schedule and the impact of operations and managed charging on electric grid emissions as an electric storage resource.

## 2. Literature Review

There are limited examples of actively managed V2G programs in the United States, therefore quantified impacts are based on simulation models. The intention of this study is to develop a methodology to quantify the grid and environmental impacts of electric school buses and asses the impact of the extent to which electric school bus fleets offer mutually beneficial advantages for electric grid operators and school route transportation. A number of other studies have used models to demonstrate the peak-shaving benefits of energy storage including V2G with private consumer vehicles and transit buses. However, private vehicles and transit operators have unique conditions that may reduce the advantages of a managed school bus fleet. To our knowledge, no previous studies have modeled the impacts of an electrified school bus fleet which could provide the most stable and predictable peak shaving based on typical school bus behavior.

A related case study to the one presented is conducted by Wellik et al. who describe the grid benefits of public transit buses in Austin, Texas (Wellik et al., 2021). The paper assesses the ability for V2G transportation systems to respond to utility operational challenges in utilizing renewable energy sources. The authors find that V2G services can provide an additional 2% of emissions reductions compared to uncontrolled charging of electric buses. Another case study of transit buses is presented by Mohamed et al. who simulate the charging demand of electric transit buses in Belleville, Ontario (Mohamed et al., 2017). This case study focuses on the impacts of uncontrolled charging on the grid by comparing unidirectional charging infrastructure with various power ratings. The model presented determines the charging demand from a fleet of transit buses based on energy consumption from daily routes and outputs a load profile resulting from uncontrolled charging. The conclusion is that fast-charging is the optimal infrastructure for a transit bus fleet to have the lowest impact on the grid. However, with school bus routes, the schedules are often fixed in a way that could benefit peak charging—when solar electricity generation increases in the middle of the day, the buses are often parked. Secondly, the buses can act as controlled storage after school-bus afternoon drop-offs. We seek to expand upon studies that focus on public bus routes by developing a new methodology for school buses that operate on shorter, less frequent routes and could simultaneously provide bidirectional charging.

Greenblatt et al. consider the grid benefits of all electric vehicles, including school buses, that are predicted to be in operation in the MISO region in the year 2039 (Greenblatt and McCall, 2021). The authors use V2G-Sim to show that bidirectional charging of electric vehicles can flatten the load profile by 62% for the region. The authors note that school buses are idle for a large portion of the day and therefore are “ideal” for V2G services.

A study by van Triel et al. analyzes the reduction of curtailment of excess solar power in California by charging V2G vehicles with the excess power and discharging during periods with low or no solar power (van Triel and Lipman, 2020). The authors utilize V2G-Sim to model future charging demand and find that the annual charging demand for the state could reach as high as 6.6 TWh by 2030. The results show that curtailment can be reduced by 65% and that vehicles can provide 50 GWh of storage using V2G services. According to the authors, the storage capacity of electric vehicles would be equivalent to $26 billion.

V2G-Sim is also utilized by Wang et al. who examine V2G revenues in California under deep decarbonization (Wang and Craig, 2021). The authors use V2G-Sim to maximize net profits by deciding whether to sell electricity to the grid by discharging, buy electricity by charging, or sell regulation reserves to the grid. The results show that vehicle owners using V2G services can reduce their annual electric charging costs by $32-$48 per vehicle by selling electricity back to the grid during peak times.

Hanus et al. explore solar photovoltaics as a means of decarbonizing educational buildings in the United States (Hanus et al., 2019). The study investigates the potential of solar panels on a per-building basis and finds that 75% of electricity needs can be met with zero-emission solar power. The associated carbon dioxide ($CO_2$) emissions reduction is 28% for the education sector although the total emissions does not include those from school buses. If solar panels were installed on educational buildings, they could be part of the electric school bus ecosystem. This would ensure that buses are charged with low-carbon electricity. Furthermore, integrating electric school bus planning as part of the overall building electrification plan could increase overall cost savings and synergistic benefits. Educational buildings also provide useful demonstration sites for interactive learning activities.

Pimm et al. report the potential peak shaving from small-scale, residential storage in the United Kingdom (Pimm et al., 2018). With 2-kWh batteries per residence to support demand during peak hours, 50% of the load at low-voltage substations can be reduced. The authors caution that forecasting of the load and control of the batteries cause uncertainty in the peak shaving results.

García-Olivares et al. quantify the potential energy reduction from a non-fossil fuel based transportation sector including personal, commercial, and public transport vehicles (García-Olivares et al., 2018). The study finds that a 100% renewable transportation system would reduce energy use by 18% with the largest contribution coming from electric road vehicles. While they do not consider all life-cycle energy needed to support and maintain the infrastructure for a new electric transport system, they conclude that electrically powering road vehicles is more efficient than relying on fossil fuels. Emissions reductions are not quantified in the García et al. paper, but can be an assumed consequence of energy efficiency.

Zhang et al. illustrate operational grid benefits based on models of consumer trends in the EV market in the midwestern United States (Zhang et al., 2020). They find that V2G can shave up to 23 GW from the region's peak load based on predictions of EV ownership and driving patterns in the year 2038. Coignard et al. model renewable integration opportunities of V1G and V2G implementation in California (Coignard et al., 2018). The authors find that curtailment of excess solar power during the day could be offset by controlled charging, rendering expensive stationary storage unnecessary.

One study investigates the grid and environmental benefits of unidirectional controlled charging of non-specific EV. Foley et al. simulate grid impacts of EVs in Ireland to demonstrate how off-peak charging of vehicles is preferable to on-peak charging based on electricity emissions and cost variations throughout the day (Foley et al., 2013). The emissions benefits are narrow since off-peak charging remains reliant on natural gas and coal. However, the results show that EV charging affected the generation portfolio by reducing wind curtailment thereby reducing overall emissions.

A group of studies have analyzed electrification of vehicle fleets on electric load profiles and capacity reductions. However, most of these studies have focused on aggregated personal vehicles or fleets that are managed by individuals. Electric school buses require fixed schedules to pick-up and drop-off students. This study addresses a knowledge gap by focusing on the timing and execution of serving electric school bus routes and their impacts on the electric grid and peak shifting. Vehicle-to-grid services are being evaluated as part of the revenue stream for utilities and school districts. The paper uses an open-source and rigorous assessment of vehicle charging using the V2G-Sim model and historic load profiles to conduct a peak shifting assessment. Moreover, this study fills a research need by connecting the active and managed charging of electric school buses with an impact on net load and greenhouse gas emission reduction potential. Therefore, this study develops a bidirectional V2G charging model to understand effects on grid operations and provides a quantitative basis to evaluate greenhouse gas emissions across baseline, status quo electric demand and school bus operations. To our knowledge, prior studies have not optimized bidirectional charging with a peak net load analysis to estimate fleet-wide emission reductions from school buses alone. School buses are an important fleet for vehicle electrification as they are owned and operated typically by single entities and retain ownership of thousands of vehicles. The methodology developed in this study can be applied for school bus integration nationally and internationally.

Load data, electric school bus specifications, and charger specifications are used to determine optimized shaving of peaks in the load. The methodology applies net load changes with a V2G simulator, which is a novel way to evaluate electric school bus power demand, and builds on previous work based on peak shaving studies, such as Greenblatt et al. (Greenblatt and McCall, 2021). Another output of this model is the quantification of the extent to which V2G school buses can reduce peak loads, which would allow the state to utilize less natural gas electricity or potentially retire peaker plants earlier than planned in addition to providing cleaner transportation services to the public. For more details about how this study differs from previous work, see Table 1.

## 3. Methods

### 3.1. Study Overview

This study develops a model to simulate electric school bus charging by modifying Vehicle-to-Grid Simulator (V2G-Sim) to maximize total energy shaved during peak demand periods using a fleet of coordinated electric school buses. The electrical load data for one year are first used to examine whether buses will be connected to the grid during the hours of highest electrical demand. This analysis is accomplished by determining what days and times those hours occur and if those hours coincide with public school bus routes. In the event that those hours overlap, electric buses could not be considered stationary storage assets that are capable of supporting the retirement of a peaker plant since the level of generation capacity is expected to support the highest demand at any given time. During other hours, school buses are considered stationary storage assets by the model. After the number of hours and capacity of available storage in the buses is determined, the modified version of V2G-Sim is run to determine the daily peak shaving capabilities of the fully-electrified fleet during three representative scenarios– a summer day, a winter week day, and winter weekend day. These are the three major categories of school bus schedule shifts because it represents a day when school is out of session in summer, in-session during winter, and a winter holiday. The data output is a spreadsheet which includes the power provided by the fleet and the new optimized load profile for the day. These data are used to find the total energy shaved during peak periods, which is considered as a reduction of natural gas use if

**Table 1**
Comparison of content of literature review and this paper with the author of the reviewed paper, their research focus, the research focus of this paper, and the significance of the current focus.

| Author | Focus of Study | Focus of this Study | Significance |
|---|---|---|---|
| Wellik et al. (Wellik et al., 2021) | Transit buses | School buses | School buses are stationary more often. |
| Mohamed et al. (Mohamed et al., 2017) | Uncontrolled charging | Controlled charging | Controlled charging offers grid stability. |
| Greenblatt et al. (Greenblatt and McCall, 2021) | All EV | Only school buses | School buses are the ideal candidate for V2G. |
| van Triel et al. (van Triel and Lipman, 2020) | V2G for solar curtailment Reduction | V2G for peak shaving | Solar curtailment is not currently an issue for many states. |
| Wang et al. (Wang and Craig, 2021) | V2G revenues under deep decarbonization | V2G GHG emission reduction potentials for school bus fleet | Despite potential declining revenues for V2G with increased renewable penetration, operational grid benefits from less variable peak demand and significant GHG emission reductions. |
| Hanus et al. (Hanus et al., 2019) | Decarbonizing educational Buildings | Decarbonizing educational transportation | Electric buses eliminate emissions that directly impact student health. |
| Pimm et al. (Pimm et al., 2018) | Residential storage | EV bus storage | Fewer decision makers control more resources. |
| García-Olivares et al. (García-Olivares et al., 2018) | Overall energy reduction from V1G | Peak energy reduction from V2G | Better grid stability can create additional avoided emissions. |
| Zhang et al. (Zhang et al., 2020) | Consumer EV | Public EV | Fewer decision makers control more resources. |
| Coignard et al. (Coignard et al., 2018) | Support for renewables | Support for renewables not considered | Future work |
| Foley et al. (Foley et al., 2013) | Support for renewables | Support for renewables not considered | Future work |

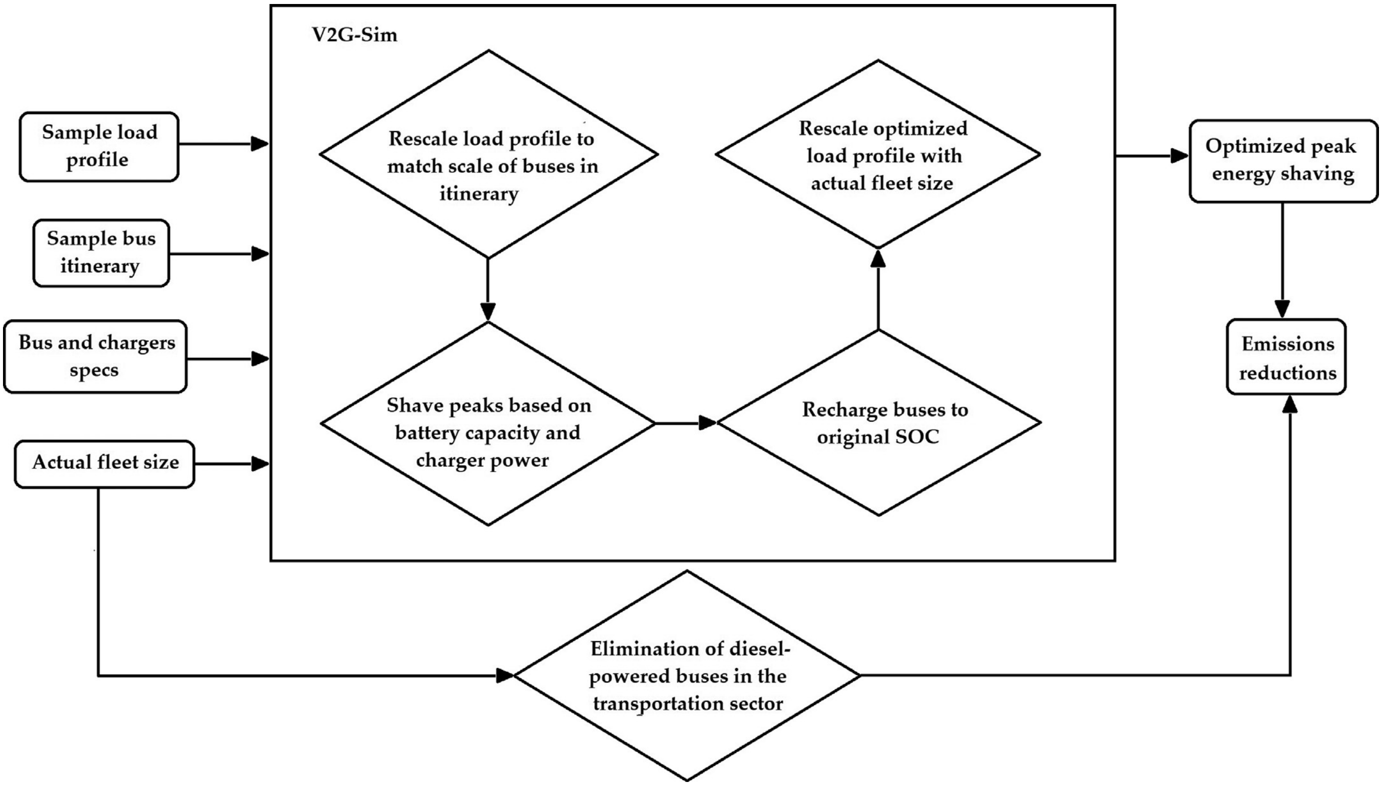

**Fig. 1.** Overview of methodology for determining operational grid benefits and $CO_2$ emissions reductions using V2G-Sim for peak shaving.

recharging batteries is powered by low-carbon sources. The output spreadsheet also provides the unoptimized load profile. A sensitivity analysis is conducted to demonstrate how variations in the fleet size, battery capacity, and charger power impact the peak shaving results. Additionally, avoided emissions within the transportation sector are calculated by multiplying the fleet size by the emissions of diesel buses.

To complete each simulation, the model follows the sequence shown in Fig. 1. The required inputs are a sample load profile, a sample one-day vehicle driving itinerary, the bus battery capacity, the charger power rating, and the actual fleet size. The ratio of vehicles in the sample itinerary to the actual fleet size is used to rescale the load profile with a ten-minute resolution, saving computational time. The load is then optimized under the constraints of the battery capacity of the vehicles and power rating of the chargers. The initial optimization is then scaled up to represent the actual fleet size at minute resolution to model the higher resolution, aggregated grid impacts. The aggregated energy reduction is converted into an emissions reduction by multiplying the shaved energy by an emission factor for the peak load.

To optimize load profiles using electric school buses with DC fast chargers, modifications from previous models are made to allow for rapid-fast chargers and increase the battery capacity. The specifications of the bus batteries, motors, and chassis are included to accurately calculate energy consumption from driving and energy delivery from discharging to the grid. DC fast chargers have a higher power capacity than other charging profiles previously studied. Additionally, a driving itinerary specific to local bus schedules is created to dictate when buses are connected to the grid. Detailed information about the creation of the itinerary is found in Section 3.3.3. The code to accommodate Lion Type C electric school buses as well as sample itineraries and load data spreadsheets can be accessed via the open-access GitHub repository for further use https://melrenell.github.io/V2G/. The "README" file explains how to install the software on a local hard drive.

### 3.2. Software

This section describes the V2G simulation Python tool called Vehicle-to-Grid Simulator (V2G-Sim) that is utilized to optimize peak shaving of load profiles after inputting driving patterns and charging needs (Lawrence Berkeley National Laboratory 2020). V2G-Sim focuses on individual vehicle charging and this analysis aggregates individual vehicle charging behavior across a fleet and profile of many school buses connected to the same grid. The driving and charging behavior of individual EVs generates new charging profiles in terms of power and energy duration, and estimates impacts of increased electric vehicle deployment (Lawrence Berkeley National Laboratory 2020). The model is scalable to simulate impacts for any number of vehicles up to 1 million EVs (Lawrence Berkeley National Laboratory 2020). The original version of V2G-Sim functions with hard-coded specifications for the vehicle and charging infrastructure which are not applicable to fleets of larger capacity vehicles. This analysis expands the capability of V2G-Sim's vehicle power and energy capacities and inclusion of sample school bus itineraries to simulate fleets of electric school buses.

This application based on V2G-Sim uses the load profile, a sample bus itinerary, the actual fleet size, V2G charger specifications, and bus battery capacity as inputs to demonstrate the additional load resulting from unoptimized charging of the electrified fleet as well as the peak shaving potential resulting from optimized V2G charging and discharging. The sample bus itinerary is used to determine when the fleet is connected to the chargers and when the buses depart for routes. The software assumes that the batteries are fully charged at the start of the simulation and uses the sample bus itinerary to determine the state of charge of the bus at the time it reconnects to the charger based on its battery capacity and distance traveled. In this study, a survey of school bus routes was conducted to identify and estimate timetables for charging and discharging, and distances traveled.

The model has two optimization method options: peak shaving (Eq. (1)) and ramp mitigation (Eq. (2)). Peak shaving refers to the minimization of the overall maximum power demand in the daily load profile, where storage is used to absorb as much power to reduce the peak as possible. Ramp mitigation optimizes by minimizing the rate of change of the load. This method is useful for load profiles that are dynamically affected by excess solar energy during the day because as the sun sets, residential demands rise causing a steep ramp. This situation requires a sufficient amount of quick-dispatch electricity to accommodate increasing demand over a short time interval. For ramp mitigation, the slope of the ramp, sometimes referred to as the ramp rate, is a key metric to reduce overall stress on the electric grid. Peak shaving, on the other hand, optimizes by flattening the peak of the daily load by discharging V2G vehicles and re-charging in the trough which is appropriate for the shape of North Carolina's load profile. Peak shaving, for this study, is a different charging algorithm and strategy than ramp mitigation, and reduces the overall change in power demand for a daily load profile. For this reason, the peak shaving optimization is used in this study to minimize daily maximum power demanded on the grid. When peak power is supplied by natural gas plants, reducing natural gas requirements would have the greatest operational benefit on the power grid in terms of environmental impact reduction, as the peak demand determines the amount of natural gas combusted rather than the slope of the change in power demand.

Once these inputs are provided, the software can be run to optimize the load profile using buses as storage for peak shaving. V2G-Sim uses the Gurobi Optimizer package for the optimization step. V2G-Sim uses Gurobi's dual simplex algorithm to solve the continuous model. Once the user chooses a optimization method, the software operates under the constraints shown in Eqs. (3), 4, and 5. Eq. (3) states that the charging/discharging rate cannot exceed the charging/discharging power rating of the charger. Eq. (4) states that the total energy charged from or discharged to the grid over any single time period (peak or valley) is limited by the total battery capacity of the fleet and that the maximum power difference between the original and optimized curves cannot exceed the total power of the chargers. Equation 5 states that the total energy charged at the end of the simulation is limited by the maximum power of the chargers.

Peak shaving minimizes the value

$$\sum_t^T \left[ netload(t) + \sum_i^V P_{charge,i}(t) \right]^2 \tag{1}$$

and ramp mitigation minimizes the value

$$\sum_t^T \left[ \Delta netload(t) + \sum_i^V \Delta P_{charge,i}(t) \right]^2 \tag{2}$$

where $P_{charge,i}(t)$ is the power charged or discharged for vehicle $i$ at time $t$, $T$ is the number of time intervals, and $V$ is the number of vehicles in the model. The optimization is subject to the following constraints:

$$P_{min,i} < P_{charge,i} < P_{max,i} \tag{3}$$

$$(SOC_{min,i} - SOC_{init,i}) * \frac{E_i}{\Delta t} + \sum_{t=1}^{T} C_i^t \le \sum_{t=1}^{T} P_{charge,i}(t)$$
$$\le (SOC_{max,i} - SOC_{init,i}) * \frac{E_i}{\Delta t} + \sum_{t=1}^{T} C_i^t \tag{4}$$

$$\left(SOC_{final,i} - SOC_{init,i}\right) * \frac{E_i}{\Delta t} + \sum_{t=1}^{T} C_i^t \le \sum_{t=1}^{T} P_{charge,i}(t) \tag{5}$$

where $P_{min,i}$ is the maximum discharge power, $P_{max,i}$ is the maximum charge power, $SOC$ is the state of charge from 0% to 100%, $E_i$ is the battery capacity of vehicle $i$, and $C_i{}^t$ is the battery consumption of vehicle $i$ at time $t$. For a full list of the variables, see the Nomenclature.

**Table 2**
Capacity options and associated ranges of Lion C school bus.

| Range | Capacity |
|---|---|
| 100 miles/150 km | 126 kWh |
| 125 miles/200 km | 168 kWh |
| 155 miles/250 km | 210 kWh |

After the simulation is complete, plots of original, unoptimized, and optimized load profiles are generated and a spreadsheet of the data is compiled. The spreadsheet includes the unoptimized and optimized power provided/consumed by the fleet in one minute intervals and the unoptimized and optimized load profiles for the day.

### 3.3. Data

#### 3.3.1. Electric Bus Specifications

School bus specifications were provided by the electric bus manufacturer Lion Electric (Lion Electric 2020). Assumptions used in this study are based on the Lion Type C school bus because the company provides the most detailed bus specifications and is responsible for delivering the largest electric school bus fleet in the U.S. (BusinessWire 2020). These specifications include but are not limited to battery capacity, range, depth of charge, and price. The bus is available with 3 range/capacity options as shown in Table 2. The 126-kWh option was chosen as the most suitable option because it is the least expensive model and because individual bus routes are estimated to remain under 70 km. The nominal consumption rate is calculated by dividing the battery capacity by the maximum range of the vehicle. For the selected option, the consumption rate is 0.84 kWh/km. V2G chargers are assigned a 60-kW maximum power rating (Coritech Services. n.d).

#### 3.3.2. School Bus Itinerary

For the purposes of developing representative school days under different operating conditions, a sample itinerary of 25 school bus driving patterns was created assuming buses traveling between 6:00AM and 9:30AM for morning routes and between 2:00PM and 5:30PM for evening routes. These assumptions are based on school hours in four North Carolina county school districts (Onslow, Moore, Charlotte-Mecklenburg, and Alexander) with populations ranging from 37,500 to 1.11 million (Onslow County Schools 2020; Moore County Schools. School Hours. 2020; Charlotte-Mecklenburg Schools 2020; Alexander County Schools 2020) and average student ride times between 15 and 50 min (North Carolina School Bus Safety). The school bus itinerary with charging/discharging schedules and driving distance is included in Supplementary Materials Spreadsheet 1. The schedules are based off real average approximations of travel time and power consumption for an electric school bus. Charging infrastructure can be installed at the current location of bus fleet parking and total route distances are assumed to be unaffected by the transition from diesel to electric. The bus parking lots represent a home base and are designed to maximize fleet management.

To minimize the number of buses needed in a district, the same fleet of buses services first elementary schools, then middle schools, and finally high schools for both morning and afternoon routes as the start times and end times are often staggered with high schools and middle schools beginning earlier than elementary schools, which reflects typical school district operations. Times used for the route itinerary neglect extra routes for after-school programs, field trips, and any other trips performed by buses since often times these programs are services by separate "activity buses". The itinerary is representative of rural and urban school systems in North Carolina as the scheduling of charging and driving likely occurs around the same time. However, counties with a lower population density may experience longer bus routes which would expand the range of drive times.

### 3.3.3. Load Profile Inputs

Electric grid load profile inputs for 2006 to 2018 are provided on an hourly resolution by Federal Energy Regulatory Commission Form 714 (Federal Energy Regulatory Commission 2020). The load data in this analysis are for the state of North Carolina. Data for the year 2018 are selected for use in V2G-Sim because they are the most recent data available and therefore the best estimation of current and future electricity use in the state – and represent activities pre-COVID-19 virtual school disruptions.

Load profile data are restructured in two ways: in a time-ascending order ("load curve") as seen in Fig. A.10 and in a load-descending order ("load duration curve"), represented in Fig. A.11. Historical load duration curves are generated for all years between 2006 and 2018 for analysis of trends in the peak annual hours. Average load curve data for 2018 are interpolated to minute-resolution (see Fig. A.12) for optimization in V2G-Sim.

## 3.4. Load Profile Analysis

Restructuring the load data in descending order highlights the absolute maximum and minimum load values and the hours per year at near-peak load. Available generation capacity must be able to supply the power needed at the absolute maximum load in order to maintain stability. To evaluate the environmental and operational energy benefits of investing in and deploying an entirely electric fleet of school buses in NC, the load duration curve for 2018 is created with and without electric school buses. Using a simulated load duration curve, the effect of large-scale electric school bus deployment during peak demand periods can be estimated.

Secondly, average single-day load profiles are generated for the summer and winter seasons of 2018. These samples were selected because they represent days with maximum electrical demand and reflect when school buses are in operation or are strictly stationary. An average load over all days of the given season is calculated and interpolated to minute resolution and input to V2G-Sim. For the winter cases, buses are active on weekdays and stationary on week- ends. The weekday scenario requires the input of the school bus itinerary. For the summer case, buses are assumed stationary at all times. Maximum power is set to 60 kW per vehicle. Peak shaving is chosen as the optimization type. Modulating the net load is helpful because it can account for different uncontrollable scenarios of electric school bus deployment. Then, a counterfactual load profile for North Carolina can be developed for when diesel school buses are utilized, developed from initial baseline conditions, as there are very few electric school buses in operation in North Carolina.

For emissions reductions calculations, it is assumed that electricity at peak hours is provided by natural gas combustion turbines and, at non-peak times, electricity comes from zero-emission electricity options since grid stability reduces the need for fast-responding fossil fuels (Duke Energy 2019). The natural gas $CO_2$ emissions factor of 423.9 kg/MWh in North Carolina is used to determine avoided emissions based on US EPA eGrid data (U.S. Environmental Protection Agency 2020). Multiplying this emission factor by the peak electricity displacement yields the emissions that could be eliminated from the electricity sector. This is expressed as:

$$EF_{peak} * \int_{t_{peak,i}}^{t_{peak,f}} \left[L_{orig} - L_{opt}\right] = E_{red} \tag{6}$$

where $EF_{peak}$ is the emissions factor of the fuel used to produce peak electricity, $L_{orig}$ is the original load, $L_{opt}$ is the optimized load, $E_{red}$ is the reduced emissions, and the bounds of integration are the times when peak shaving begins ($t_{peak,i}$) and ends ($t_{peak,\ f}$).

# 4. Results

## 4.1. Historic Annual Peak Load Analysis

Fig. 2 shows the top 1% of hours and the top ten hours of 2018 which represent the steepest section of the load duration curve. The two curves represent the original load and the load with 14,000 V2G-enabled buses discharging with the 60-kW DC fast charger. The fast (dis)chargers are capable of supporting a maximum of 840-MW decrease in the load provided that all buses are fully charged and connected to chargers at the peak hours. This represents the capacity and size of a typical large coal-fired thermal power plant or several smaller natural gas combustion turbines. Under ideal conditions, 840 MW of fossil fuel generation capacity could be retired which is the equivalent of up to three of North Carolina's natural gas plants (U.S. Energy Information Administration 2019).

For 2018, 7 of the top ten electricity demand hours of the year occurred on January 2nd from 6AM to 9AM, January 5th from 6AM to 9AM, and January 7th from 8AM to 9AM. Most public schools in North Carolina returned from winter break on January 3rd in 2018, so the bus fleet would have been active for three of the top ten hours that year (Semler, 2017; Johnson, 2017). Fig. 3 shows that 26 out of 130 of the top hours occurred during the school year, during morning route times. Therefore, 20% of the hours of highest energy demand may not have been supported by V2G school buses. In order to achieve a reduction in overall generation capacity, the school buses would need to be available for discharging during the peak hours.

In 2014, 2015, and 2018, the majority of the peak annual hours occur in the beginning of the year. For each of these years, the highest demand hours occur on the coldest day of the year implicating temperature as the cause of peak hours those years. Since North Carolina counties already have systems in place for adjusting school hours for inclement weather, one solution may be to delay school start times on the coldest days of the year. The uncertainty of the logistics of this solution would mean that natural gas peaker plants would still need to be on standby to support electric heating on those days.

## 4.2. Single-Day Peak Shaving Analysis

The following section presents the results from the three different single-day cases input to V2G-Sim. The results of this section are represented in three subsections based on electric load input and bus activity: Summer Day, Winter Week Day, and Winter Weekend Day. The summer day and the winter weekend day are assumed to have no bus activity because school is not in session. In these scenarios, the bus fleet is available to interact with the grid at all times. The winter week day scenario assumes regular bus activity for morning and afternoon routes. The bus routes in the scheduling itinerary are discussed in Section 3.3.2. These three cases represent the categories of school bus operations and itineraries that occupy the majority of school bus operational hours.

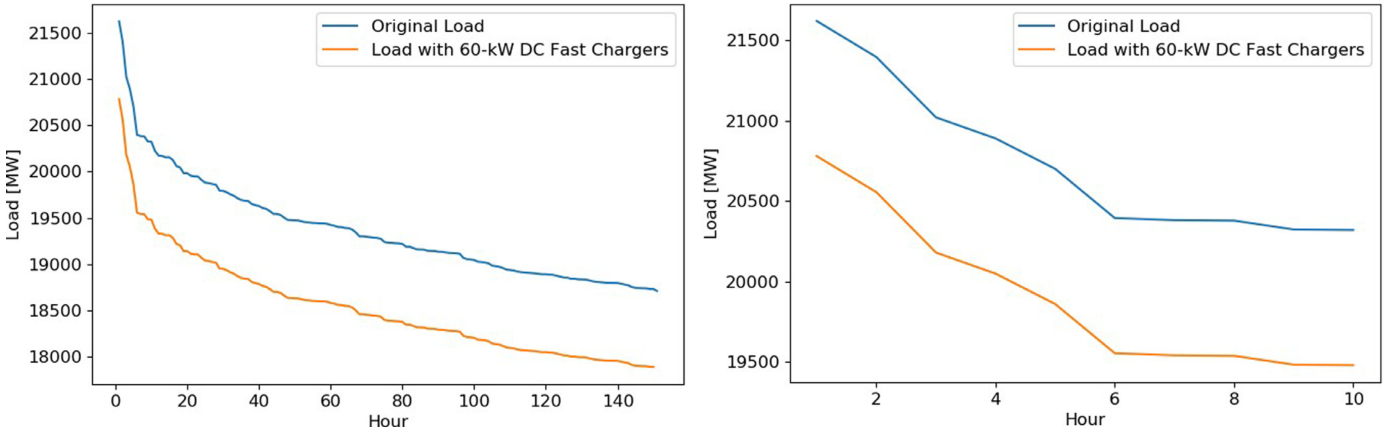

**Fig. 2.** Top 1% of hours (left) and top ten hours (right) for 2018 with 60-kW chargers available to discharge 14,000 buses.

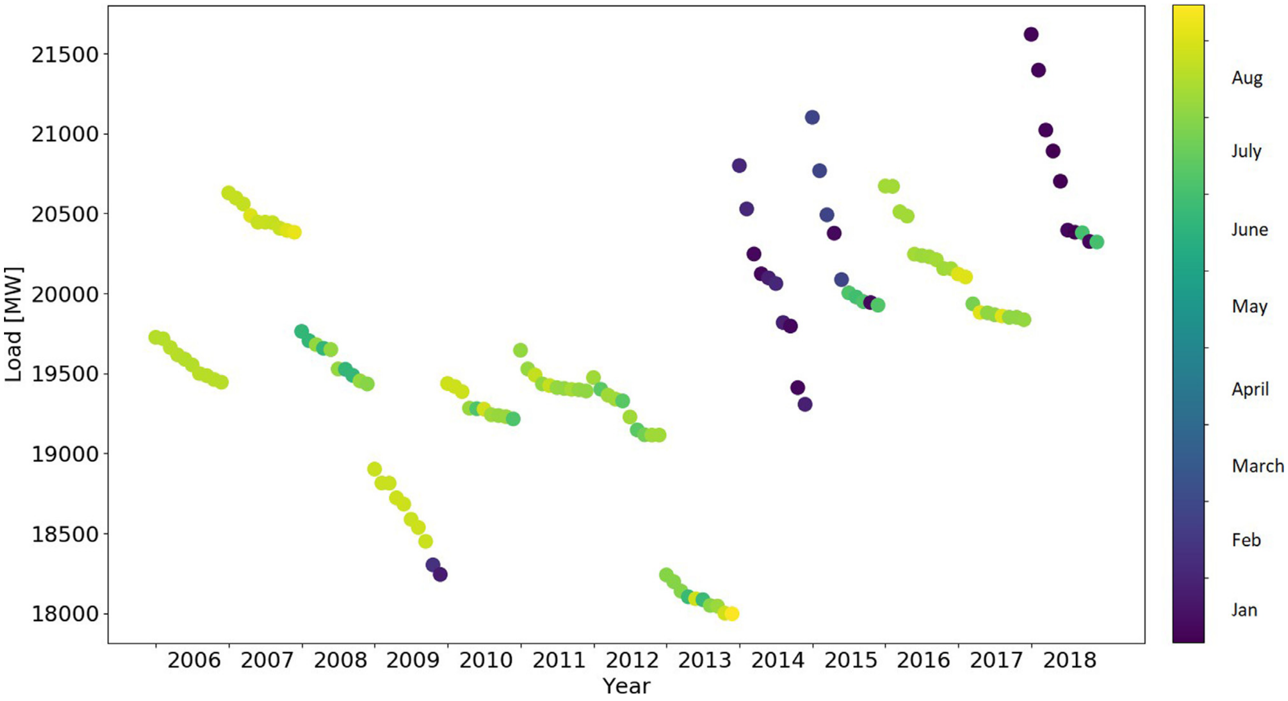

**Fig. 3.** Top 10 h for each year of data available with color map for time of year the hour occurs.

### 4.2.1. *Summer Day*

The first result from V2G-Sim is Fig. 4, a series of plots that show the power, energy, and ramp constraints plotted over the load interval (24 h). The 60-kW charger and 126-kWh battery capacity constraints are scaled by the number of buses in the itinerary which in this case is 25. The power demand results plot shows the original load and the load optimized for peak shaving to produce the “net load + vehicles” curve. For this plot, the power is scaled by a factor of 25/14,000. Each plot has a time scale of 144 min, the minutes of one day divided by the optimization time interval of 10 min. The load curve is rescaled by 14,000/25 and reindexed to 1440 min to create Fig. 5. For this plot, the ”original” and ”unoptimized” curves overlap completely because the buses are not in operation and therefore do not need to recharge. The main peak occurs between 3:00PM and 6:30PM. This load is reduced by dispatching the bus batteries to supply electricity to the grid, and the buses are recharged during the period of lower demand. The optimization shows a maximum reduction of 840 MW for the peak.

### 4.2.2. *Winter Week Day*

Figs. 6 and 7 represent the same process applied to a winter weekday. For this scenario, the bus itinerary for an average weekday is added to the model. This scenario has three possible scenarios: no electric buses (”original”), electric buses with no controlled charging and no V2G capability (”unoptimized”), and V2G electric buses that undergo controlled charging (”optimized”). For the optimized curve, the first minor peak is shaved, causing the buses to recharge during the first trough. The first major peak is not shaved because the buses are active until the end of the peak. The second major peak is shaved, causing the buses to recharge before the end of the day in order to preserve the initial state of charge.

### 4.2.3. *Winter Weekend Day*

Fig. 8 represents an average winter weekend day. For this scenario, the same average winter day load was input with no bus itinerary therefore the ”original” and ”unoptimized” curves overlap completely. Like the summer scenario, all peaks are shaved, and recharging occurs during periods of lower demand. This figure il-

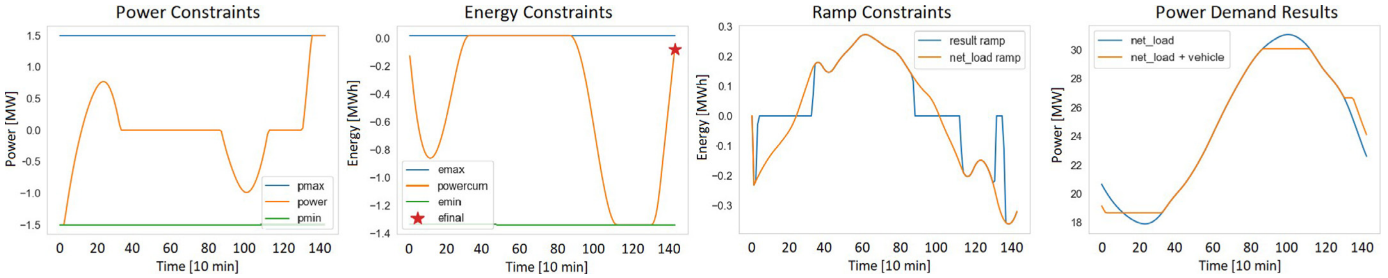

**Fig. 4.** Summer day plots. The x-axis of each plot has a time scale of 144 min, the minutes of one day divided by the optimization time interval of 10 min. (First) Power constraints. Buses are connected at all times because they are not active over an average summer day. 1.5 MW of power is available to charge (pmax) or discharge (pmin). The "power" curve is the optimized power distribution for peak shaving. (Second) Energy constraints. Each bus has 126 kWh of battery capacity. The cumulative power is also plotted with the final energy balance (efinal). (Third) Ramp constraints with the original ramp and the optimized ramp. (Fourth) Original load and optimized load.

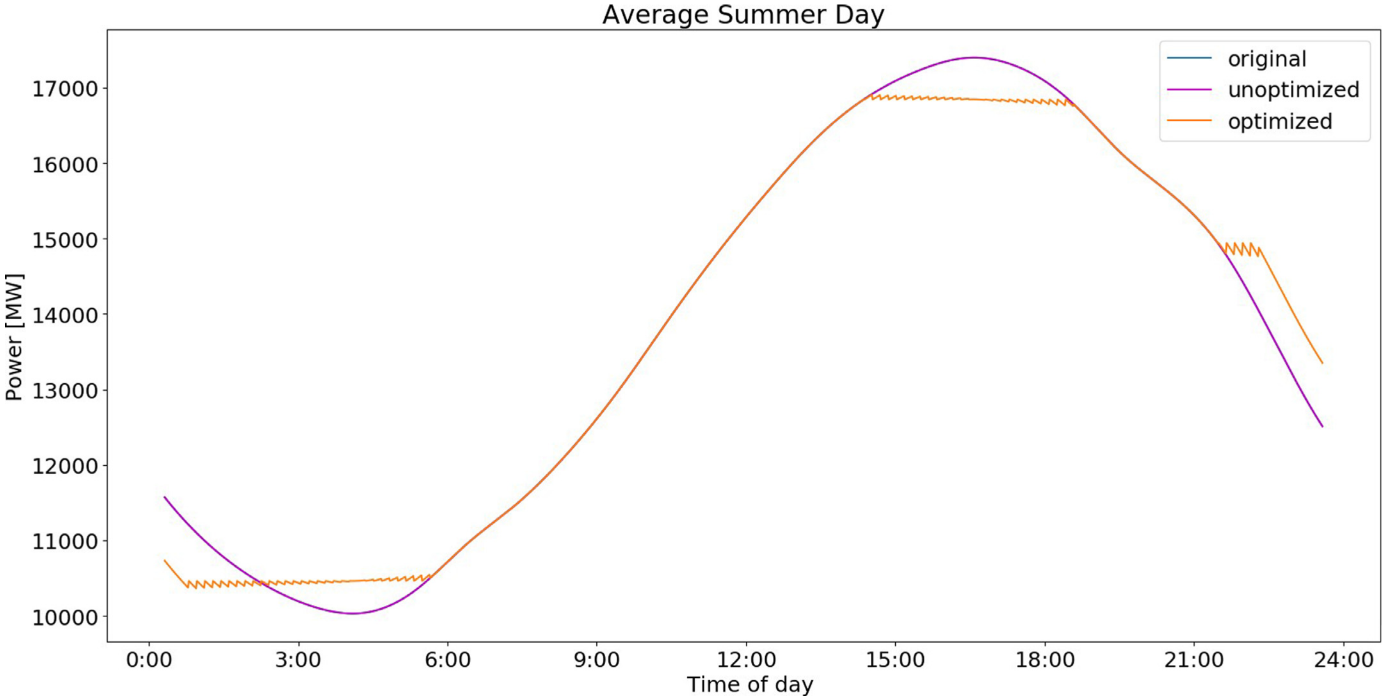

**Fig. 5.** Summer day load. The original net load (blue and purple) and the net load with 14,000 V2G school buses (orange). The original and unoptimized net load completely overlap because there is no bus activity and therefore no charging occurs to add to the original load. The "optimized" curve shows that the first peak is shaved causing the buses to recharge during the first trough. The main peak is shaved causing the buses to recharge before the end of the day to ensure that the final state of charge matches the initial state of charge.

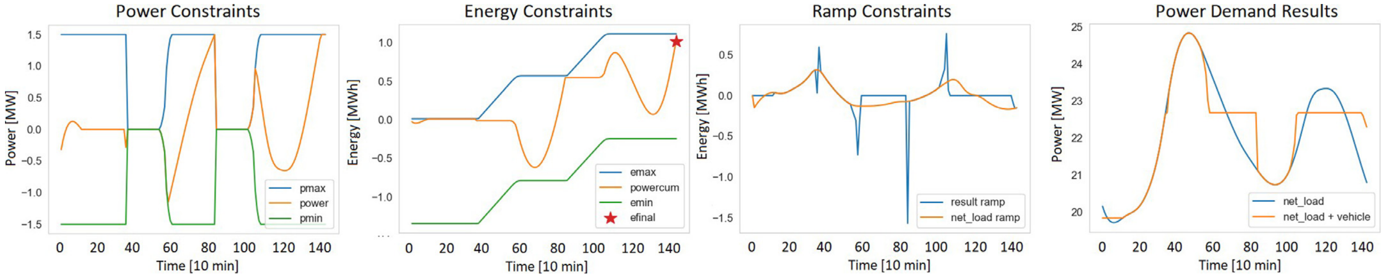

**Fig. 6.** Winter week day plots. Each plot has a time scale of 144 min, the minutes of one day divided by the optimization time interval of 10 min. (First) Power constraints. A maximum 1.5 MW (60 kW times 25 sample buses) of power is available to charge (pmax) or discharge (pmin). The "power" curve is the optimized power distribution for peak shaving. (Second) Energy constraints. Each bus has 126 kWh of battery capacity. The cumulative power is also plotted with the final energy balance (efinal). (Third) Ramp constraints with the original ramp and the optimized ramp. (Fourth) Original load and optimized load.

lustrates the additional step of finding the power that preserves the daily energy use while providing the ideal, flat load profile. The yellow regions represent the storage provided by 14,000 buses and the green regions represent the additional storage need to achieve the flat load profile. For the original output, see Fig. A.13.

### 4.2.4. Comparison

Table 3 shows the energy shifted during peak shaving for each scenario. The best scenario for energy reduction is the winter weekend when 2,664 MWh of electricity can be shaved. Compared to the average daily electricity use of a single North Carolina res-

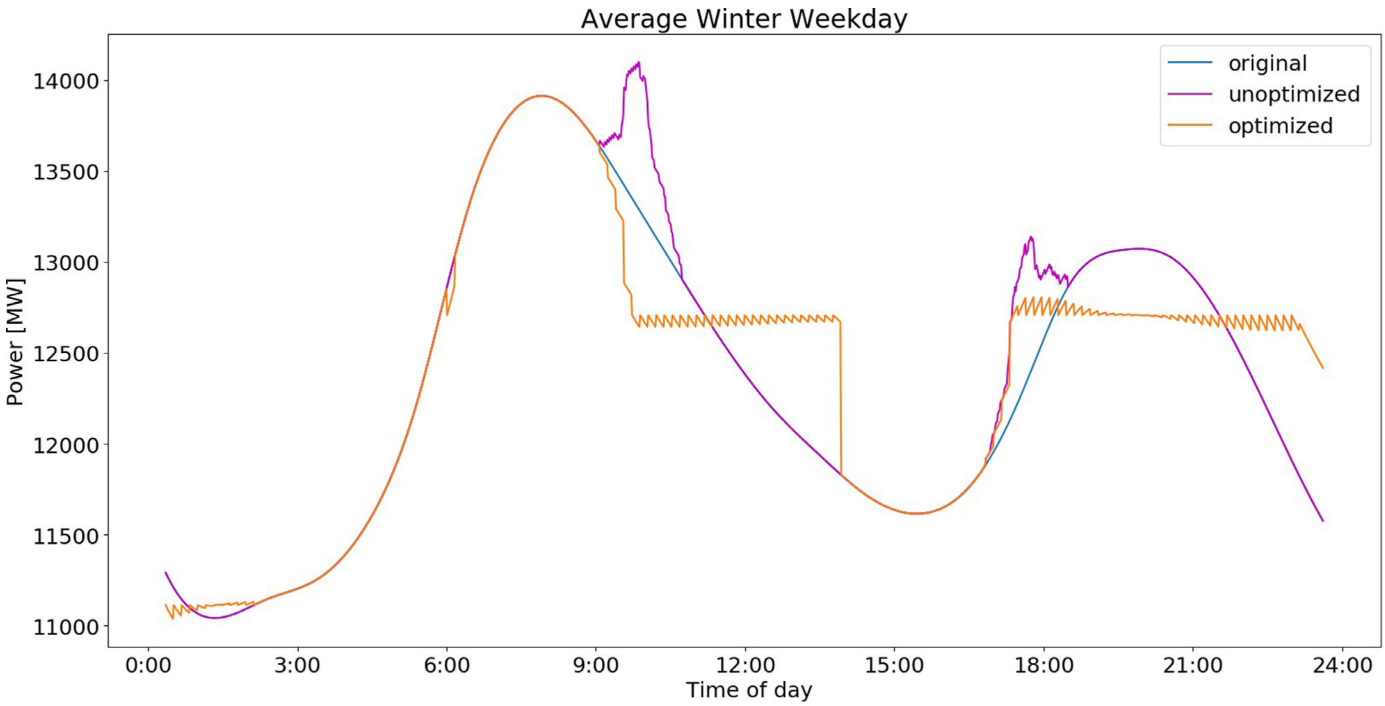

**Fig. 7.** Winter week day load. The original load (blue), the unoptimized load with 14,000 non-V2G electric buses charging with no control system upon return from driving activity (purple), and the optimized load with 14,000 V2G school buses (orange). The first peak is shaved causing the buses to recharge during the first trough. The main peak experiences shaving only at 9:00AM when buses return to charging stations. The buses reach a minimum state of charge at 11:20AM and begin recharging so that the second cycle of driving activity can begin at 2:00PM. The secondary peak is shaved causing the buses to recharge before the end of the day to ensure that the final state of charge matches the initial state of charge.

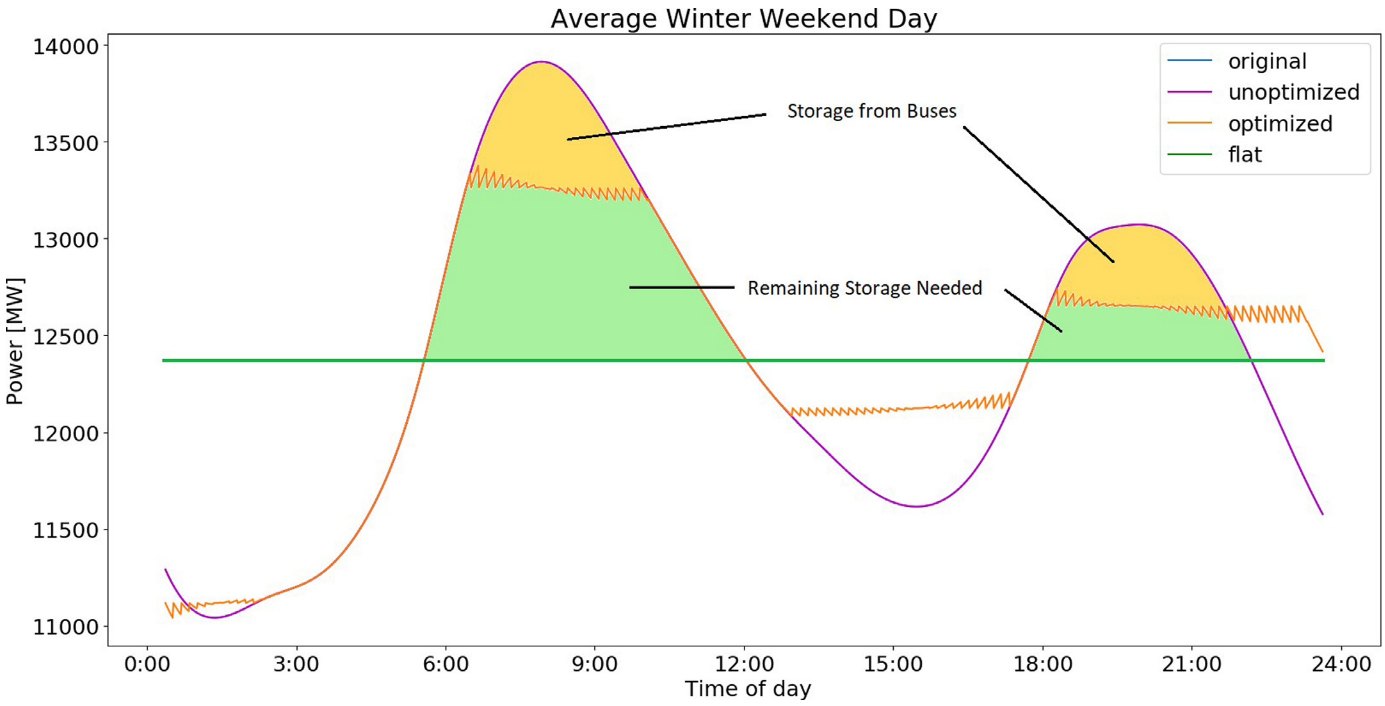

**Fig. 8.** Winter weekend day load. The original net load (blue and purple) and the net load with 14,000 V2G school buses (orange). The original and unoptimized net load are the same because there is no bus activity. The orange filled area represents the storage dispatched by buses during peak shaving. The green filled area represents the remaining storage needed to achieve a flat load profile.

**Table 3**
Energy shifted from peak shaving for the three scenarios that were modeled, the energy storage needed for a completely flat daily load profile, and the percent of the storage needed attained by the optimization.

| Scenario | Energy Shifted [MWh] | Storage Needed for Flat Load [MWh] | Percent Attained |
|---|---|---|---|
| Summer Day | 2,487 | 28,260 | 8.8% |
| Winter Week Day | 1,654 | 8,616 | 19.2% |
| Winter Weekend Day | 2,664 | 8,616 | 30.9% |

idence (U.S Energy Information Administration), the peak energy reduction is equivalent to 75,000 homes. The table also shows energy storage needed for a flat load profile and the percent of needed storage that buses could contribute. For a visual representation of the storage needed for a flat load profile, see Fig. 8.

### 4.2.5. Sensitivity Analysis

The winter weekend scenario resulted in the greatest value of peak shaving which suggests that the load profile of this day is the most sensitive to the input parameters. Therefore, a sensitivity analysis was conducted using the winter weekend scenario while varying the fleet size, the bus battery capacity, and the charger power, raising and lowering each by 50%. Under the conditions set for the six scenarios, charger power is the limiting factor when comparing the decreased parameters whereas the fleet size and the battery capacity of the buses are the limiting factor when comparing the increased parameters. This sensitivity occurs because the fleet size and the total battery capacity are directly proportional to the maximum energy available for any single period (peak or valley) as described in Eq. (4) while the total power at any given time is limited by the 14,000 60-kW chargers as described in Eq. (3). However, increasing the battery capacity beyond 50% in the model results in peak shaving that no longer flattens the load profile. Optimally flattening peaks with 210-kWh buses only requires an 11% increase in power even though the battery capacity is 67% larger. This suggests increasing the charger power could be a strong area for further research and development as faster and more powerful chargers could more easily flatten peaks rather than increasing battery energy capacities.

### 4.3. Greenhouse Gas emissions

Assuming that peak load is provided by natural gas with a $CO_2$ emission factor of 424 kg/MWh, the $CO_2$ emissions are calculated by taking the difference between the two curves at the peaks. The 424 kg/MWh emission factor multiplied by the peak electricity displacement yields the emissions that could be eliminated from the electricity sector. The avoided emissions results are 1,054 t of $CO_2$ per summer day, 1,129 t per winter weekend day, and 701 t per winter weekday if the recharging load is powered by a low-carbon source. Therefore, V2G electric school buses can at most reduce 0.36% of North Carolina's 317,000 daily metric tons of $CO_2$ emissions (https://www.eia.gov/environment/emissions/state/).

The daily $CO_2$ emissions saved from replacing diesel buses with electric ones is determined using Eq. (7) where $EF_{diesel}$ is 22.4 pounds of $CO_2$ emitted per gallon of diesel (EIA 2016), $FE_{diesel}$ is 6.2 miles per gallon fuel economy for a diesel bus (DOE. n.d), and $d$ is a distance traveled of 12,000 miles per 180-day school year (DOE. n.d). The $CO_2$ emissions saved from replacing diesel buses with electric ones is 0.11 t of $CO_2$ per bus per school day. If all 14,000 buses are replaced, emissions savings would be up to 1,530 t of $CO_2$ per day.

$$\frac{EF_{diesel}}{FE_{diesel}} * \frac{d}{180} = E_{red} \tag{7}$$

Charging 14,000 electric buses would result in an additional 1,234 MWh per school day. Uncontrolled charging would create peaks similar to the "unoptimized" curve in Fig. 7. These peaks would likely be supplied by natural gas peaker plants resulting in 523 t of additional $CO_2$ emissions per day. This offsets the reduction from replacing diesel with electric by 34.2%.

Comparing all of the results shows that the winter season can have a higher impact on emissions due to the avoided emissions from operating non-diesel buses even though the peak shaving opportunity is reduced due to bus activity on winter weekday mornings (Fig. 9). The winter weekday scenario generates a total $CO_2$ emission reduction of 146% from the baseline scenario of operating diesel buses. Uncontrolled, unidirectional charging of electric buses on school days creates an emissions reduction in the transportation

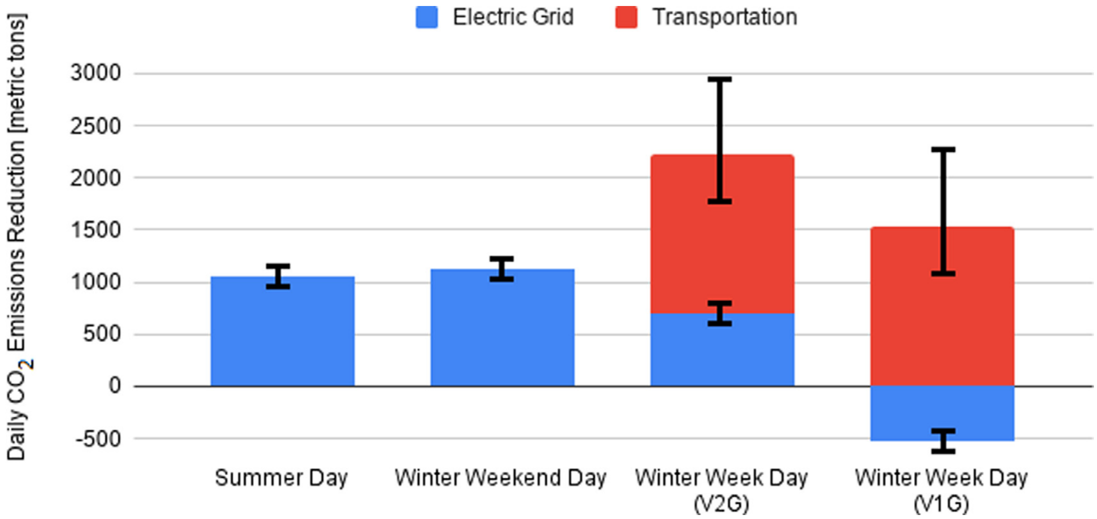

**Fig. 9.** $CO_2$ emissions reductions on a summer day and a winter weekend day when the buses are stationary all day (no transportation-related emissions reductions), on a winter week day when the buses are active, and on a winter week day if uncontrolled, unidirectional charging occurs.

sector (1,530 t/day) which compensates for the additional emissions created from the electric grid (523 t/day) which yields a net emissions reduction of 1,007 t of $CO_2$ per day, less than each of the other scenarios. The error bars in the figure are generated from the natural gas emission factor of 424 ± 11 kg/MWh for the electricity bars and from the fuel economy of 6.2 ± 2 miles per gallon for the transportation bar.

## 5. Discussion

This study develops a new methodology for modeling the best-case scenario of peak shaving with V2G school buses and determining the consequent $CO_2$ emissions reductions. The model assumes 100% efficiency of the bus-grid connection and 100% bus-grid connectivity outside of the morning and afternoon routes of an average school day. Due to uncertainty of when and where consumer electric vehicle charging will occur as the market grows, no changes in the load profile due to future private vehicle electrification are considered. This would not necessarily affect the results, in that peak demand periods would likely still occur during evenings, but wider availability of public chargers could allow for different types of charging patterns in the future. Emissions calculations assume shaved peaks are powered by natural gas and filled troughs are powered by low-carbon electricity sources. This methodology is used to explore the effects of controlled versus uncontrolled charging.

A fleet of 14,000 V2G school buses connected to the grid with 60-kW DC fast chargers can at most provide 840 MW of power to the state's grid. Assuming 17.5–21.8% discharging losses (Apostolaki-Iosifidoua et al., 2017) and 5% transmission losses (U.S. Energy Information Administration 2019), buses could provide 626–658 MW of power to the grid. However, peak annual hours may be trending towards early winter mornings when buses are unavailable to the grid as seen in Fig. 3. If this trend continues, buses will not be a reliable resource during peak annual hours and cannot contribute to overall capacity reduction. Ensuring buses are connected to the grid during the hours of highest demand would require shifting of school and bus schedules, at least on days of abnormally low temperatures.

Buses can have the greatest impact on peak shaving on summer days and on winter weekend days, with shavings of 2,487 MWh and 2,664 MWh respectively, because the buses are stationary and connected to the grid for the entirety of these days. On an average winter weekday, buses would only be connected to the grid during the smaller evening peak, resulting in 1,654 MWh of shaving. Avoided $CO_2$ emissions are between 700 and 1,130 t if the recharging load is powered by a low-carbon source. Without controlled charging, recharging peaks would likely be supplied by natural gas peaker plants causing an additional 523 t of $CO_2$ emissions per school day.

On a winter weekend day when the buses are most likely to be connected to the grid, peak shaving can eliminate up to 0.36% of emissions if (1) there are no losses due to inefficiencies, (2) school bus battery storage is replacing natural gas, and (3) recharging is powered by low-carbon sources. An estimated equivalent of 50,000 buses would be required to completely flatten the average winter day load profile or 170,000 buses for the average summer day load profile. Therefore, electrifying and installing V2G chargers for North Carolina's 14,000 buses would provide 8–31% of overall storage needed to eliminate peaker plants. These findings are evidence that V2G on its own is not the solution to emissions reductions but can be significant part of the grid stability solution.

Emissions reductions from a V2G school bus system would only constitute a fraction of a percent of total carbon emissions yet the reduction is significant compared to other vehicle types that are more active and therefore connected to the grid less often. Wellik et al. modeled peak shaving with public transit buses which have route schedules that conflict with the peak demand period. As a result, the authors found that emissions could be reduced by only 5% by switching from diesel buses to V2G electric buses. V2G school buses, however, can provide up to a 146% reduction in emissions compared to operating diesel buses. Other factors such as the energy mix and optimization parameters contribute to this difference, but the primary difference is the bus schedule.

Additional avoided emissions from electricity production will be achieved as the energy mix incorporates a growing percentage of renewables. However, intermittent renewables require storage for stability, and buses can decrease the capacity needed to stabilize a renewable-heavy energy mix. A fully electrified U.S. school bus fleet is 84 GWh of battery capacity which is equivalent to the daily electricity production of three natural gas power plants (U.S. Energy Information Administration 2019). This capacity is underutilized without V2G, especially during the summer months and on weekends.

Reducing peak capacity on a large-scale might require further integration of other electricity technologies such as specified storage, demand-response integration, or personal vehicle electrification which could further augment the capacity credit reduction capability of different V2G schemes. New policy designs are also needed to consider how schools and utilities could mutually benefit from a V2G school bus electrification investment. On a statewide-scale based on 2018 data, V2G demonstrates some benefits. However, if North Carolina were to double or triple wind and solar penetration on the grid, there could be a greater need to mitigate extreme peaks in electricity demand and other swings from a grid operations scale that might require coordination across different producers and consumers of electricity.

## 6. Conclusion

Electric school buses can have a positive impact on passengers' health and environmental health, and therefore are a good option for replacing traditional diesel buses if budgets allow. Some states have already begun transitioning to electric buses, and the current administration has expressed support by setting a goal for replacing all buses by 2030. However, replacing the entire fleet with EV buses will create new challenges for the electrical load. The set schedule of bus routes will cause a set schedule of additional electrical load if charging is uncontrolled which results in sharp peaks immediately after buses dock. These peaks can be avoided with V1G or V2G charging. Our methodology can be applied to other states' bus fleets and load profiles to determine the potential benefits of investing in bidirectional charging infrastructure.

The additional benefit of V2G charging is peak shaving which can mean reduced $CO_2$ emissions if fossil fuel plants are utilized less. Emissions from charging should be considered when calculating emissions reductions from the vehicle itself. For the greatest impact, charging must be powered by low-carbon electricity sources. The emissions reductions resulting from this methodology are minimal and assume that natural gas peaker plants are replaced by some zero-carbon alternative. However, future work could apply this methodology to determine a realistic model of support for intermittent renewables with school buses as stationary storage.

Maximum operational grid and environmental benefits of a fully electrified fleet can only be achieved with bidirectional charging infrastructure which requires coordination between utilities and school districts. Elements of new infrastructure include purchase agreements for the buses, software for managing communication between the buses and the grid, and bus route schedules. Other fleet and consumer vehicles can provide additional support to the grid as gasoline and diesel vehicles are replaced with EVs, but school buses remain the simplest case for launching V2G on a large scale.

A useful extension of this study can include an analysis of how low-carbon resources, especially variable renewables, affect vehicle-to-grid integration. This study uses the storage capacity of electric school buses to flatten the peak yet the ability to recharge with renewables remains unexplored. Using renewables for charging is critical to reducing emissions beyond the replacement of the diesel buses. Expanding V2G-Sim to evaluate larger fleets of transit vehicles and electric grid interactions would be useful under the context of time-of-use electricity pricing, arbitrage opportunities, and other vehicle storage applications beyond peak shaving. It would be interesting to understand whether school districts could increase revenues by implementing V2G under time-of-use vs. block rate electricity pricing, in addition to potential greenhouse gas emission reduction savings. From an emission reduction perspective, it would be useful to investigate the environmental and energetic benefits of avoided idling from diesel school buses, particularly during passenger pick-up times.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.11.029.

## Appendix A

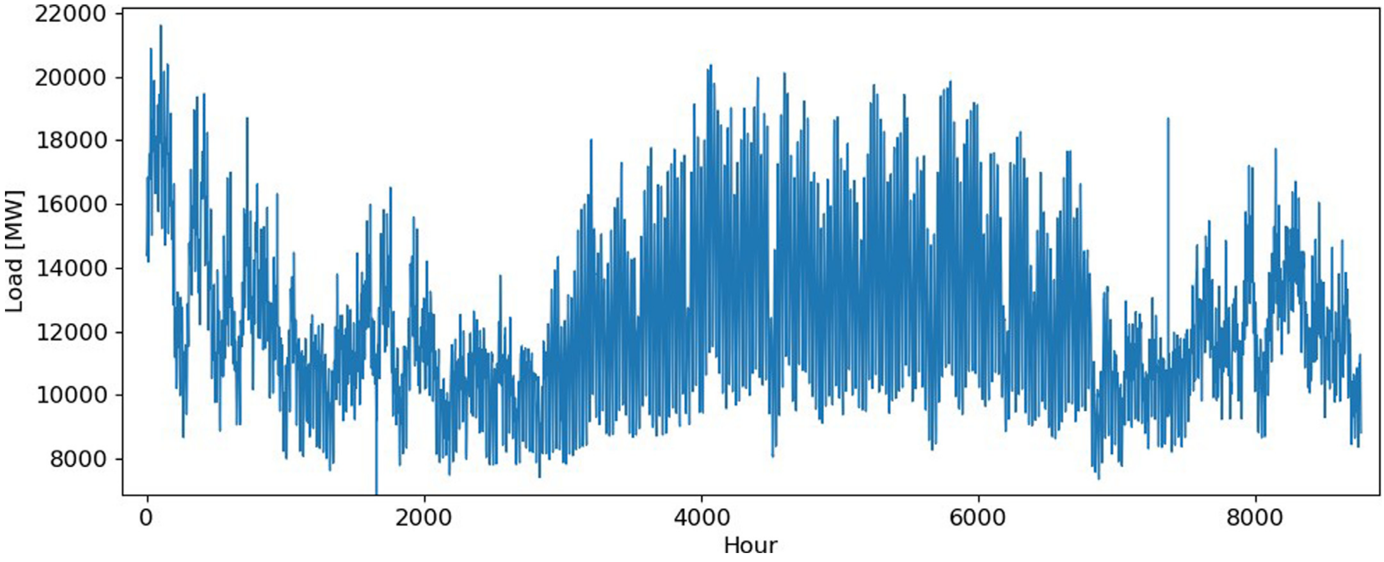

**Fig. A.10.** Electrical load for the state of North Carolina in 2018, time-ascending.

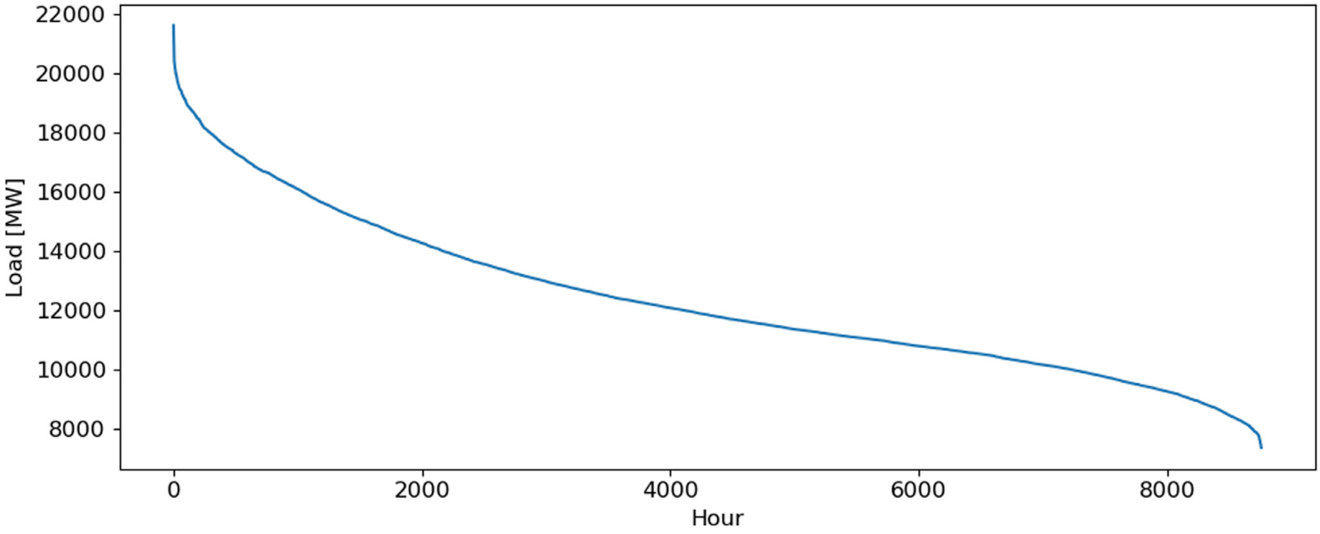

**Fig. A.11.** Electrical load for the state of North Carolina in 2018, load-descending.

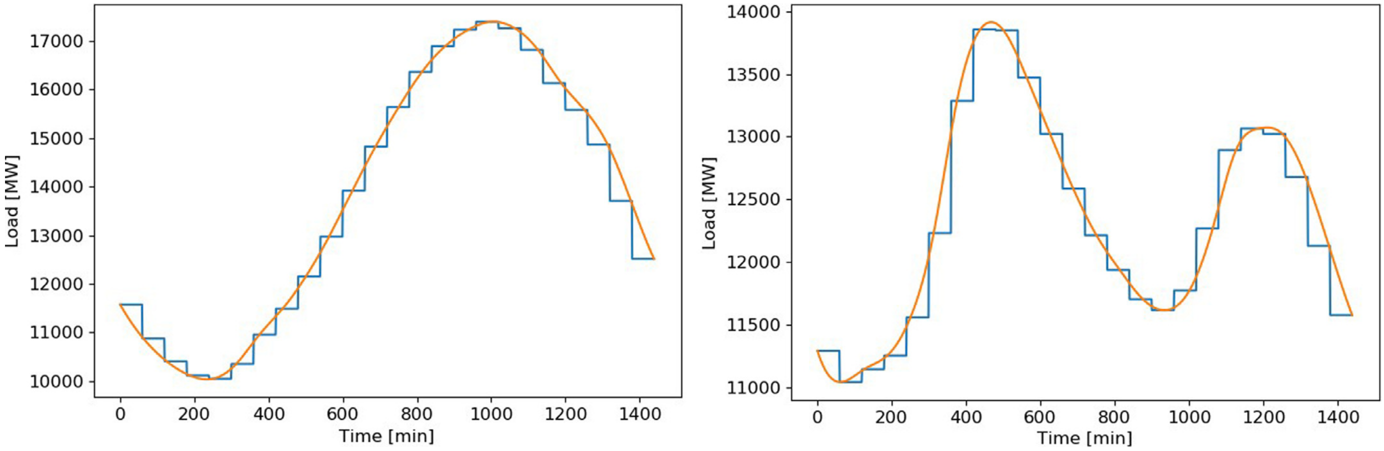

**Fig. A.12.** Average summer day load (left) and average winter day load (right) for NC, 2018.

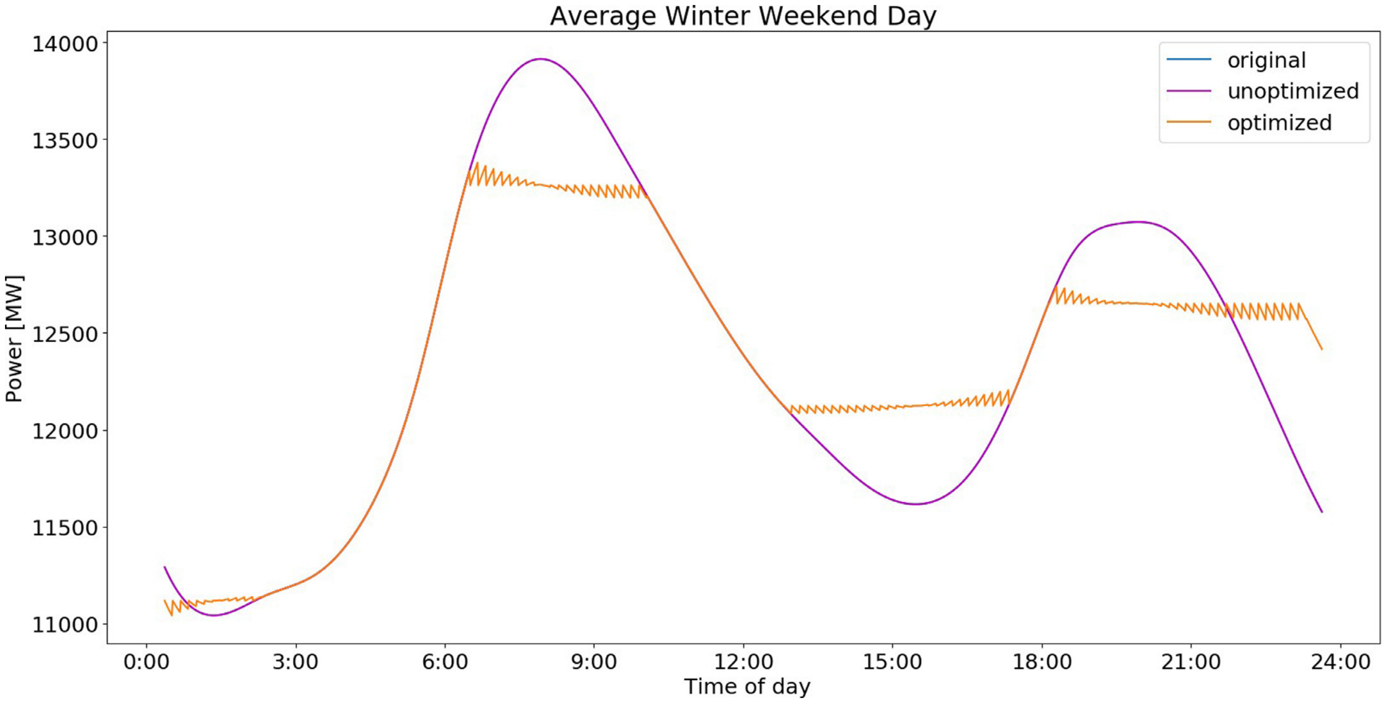

**Fig. A.13.** Winter weekend day load. The original net load (blue and purple) and the net load with 14,000 V2G school buses (orange). The original and unoptimized net load are the same because there is no bus activity. Each peak is shaved and followed by recharging during periods of lower demand.

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