UTILITY-TRANSIT NEXUS: LEVERAGING INTELLIGENTLY CHARGED ELECTRIFIED TRANSIT TO SUPPORT A RENEWABLE ENERGY GRID

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ABSTRACT

The transportation sector is a major greenhouse gas emitter. Concurrent electrification of vehicles and investment in renewable energy is required to effectively mitigate these emissions. The introduction of intermittent renewable energy sources like solar and wind at a large scale presents major challenges to utility operators. This study looks at the opportunity a Vehicle-to-Grid (V2G) Battery Electric Bus (BEB) fleet offers in overcoming these challenges. In particular, an Austin, Texas case study is analyzed to investigate the role of BEB charging in buffering sharp changes in renewable energy production to help smooth power demands from traditional energy sources of coal, natural gas, and nuclear power plants. A V2G BEB "smart charging" (SC) scenario is compared with respect to cost and emissions perspectives to a BEB "charge-as-needed" as well as a diesel bus scenario. By simply electrifying Austin's buses, without any SC strategies, the total external cost of electricity grid and bus emissions falls by approximately 3.42%, and with SC

strategies these emission costs fall by 5.64%. This is due to high renewable penetration in the region's electricity grid and because diesel is much more emitting per-unit-energy than power plants. From the transit operator's perspective, a BEB fleet costs more than a diesel bus fleet, but this could be offset by renewable energy or low-emission incentives. Finally, with SC strategies, the utility manager saved 22% of their daily cost in this case study.

Keywords: electric buses, smart charging, vehicle-to-grid charging (V2G), greenhouse gas savings

INTRODUCTION & MOTIVATION

The transportation sector is the largest greenhouse gas (GHG) emitting sector in the United States, constituting 28.9% of all GHG emissions nationally. Carbon dioxide is the major GHG emitter from the transportation sector, due to the combustion of petroleum-based products in vehicles' internal combustion engines. Therefore, moving away from petroleum-based fuels is a key to reducing emissions. From 1990 to 2017, GHG emissions from the transportation sector have risen for a number of reasons including population and economic growth, urban sprawl, and greater travel distances per capita (EPA, 2017).

Alternative, clean technology in all modes of transportation are needed to keep the earth from critical 2°C warming. Transit buses are good candidates for electrification because of their fixed schedules and routes, making it straightforward to plan around the battery range constraints (Mohamed et. al., 2017). Adoption of battery electric buses (BEBs) have been limited in scale and scope with the high upfront cost being the major barrier to entry. However, BEBs have the opportunity to minimize this initial cost discrepancy by offering lean operation. They make for an ideal application of electrified vehicle (EV) technology due to their stop-and-go nature, taking advantage of regenerative braking to capture energy that is otherwise lost to heat during traditional braking. In addition, Austin, Texas is an advantageous location for this case study as Austin rarely gets below freezing, and EV ranges can decrease by up to 50% on the coldest days of the year in the Northern U.S. (Yuksel & Michalek, 2015). Finally, BEB systems offer lowered and more predictable operating costs, delivering an important advantage over diesel buses, which can face volatile petroleum prices (Li et. al., 2018).

It is important to note that even though EVs do not emit GHG emissions directly, they do not necessarily operate "carbon-free". One must consider the carbon intensity of the grid from which the EVs are getting their electricity to charge. Depending on this carbon intensity, GHG emissions savings can be minimal when switching from diesel- or gasoline-powered vehicles to EVs, and it can even be more polluting (Kennedy, 2015). Because of this, it is important to reduce the carbon intensity of electricity grid systems in tandem with electrifying transportation. This could be achieved by increasing renewable energy system capacity to power our grids, namely, sources of solar and wind energy.

Renewable energy sources offer major reductions in GHG emissions while presenting some challenges. Sun and wind are intermittent sources that can vary dramatically over the course of each day (with the sun shining during the daytime, and wind blowing stronger at night) and throughout the year (across seasons and weather patterns). Utility managers require backup power generation during times when renewables are producing insufficient energy. It is costly to ramp up and down traditional energy sources, so managers seek to avoid this (Phuangpornpitak & Tia, 2013).

This paper develops a methodology for vehicle-to-grid (V2G) electrified transportation systems to respond to daily utility operational challenges by optimally charging and discharging to level the production of traditional energy sources. In this initial study, we look at the application of electrifying Austin's bus transit fleet. In future studies, this methodology could be expanded to other electrified transportation systems. Note that this study focused on BEBs instead of fuel-cell or hybrid electric buses based on the findings of Mohamed, Garnett, Ferguson, and Kanaroglou (2016) who reported that BEBs were the optimal fuel source for electrifying bus transit, especially for grids with high renewable penetration.

Texas leads the country in wind power with 37.5% of Austin's electricity coming from a combination of wind plus solar, compared to a national average of 10.4% in the United States (Austin Energy B, 2018; REN21, 2016). In addition, Austin has plans to achieve at least 55% renewable energy by 2025 and 65% by 2027 (Austin Energy, 2017). One could imagine a partnership between the transit provider and the utility manager wherein the transit provider receives discounted electricity prices in exchange for responding to power requests from the utility manager. This project looks at a case study of electrifying the Austin, Texas bus transit fleet, modeling this partnership between the utility and transit managers.

It should be noted that simplifications were made at the bus level in order to focus at the system-level on the broader research question: can a large-scale BEB system help support an electricity grid, particularly one that relies significantly on renewable, intermittent energy sources of solar and wind? To do this, an average value of BEB energy consumption per-mile was extracted from the literature based on bus weights and battery compositions, averaged for different terrain types. This study did not optimize bus routing and charging station locations. These parameters were considered exogenously. Results could be improved by considering this in the optimization cost function in the future. Finally, only one solar and wind profile was considered in this study. Future work should include testing this model with varied wind and solar profiles to improve the reasonability of results.

METHODOLOGY

This section describes the methodology and model framework, with two main models developed. The first is a utility manager model, which simulates the combination of energy sources the utility manager will run under certain energy demands. The overarching goal of the utility manager is to minimize the operational cost of delivering the required energy. The second model is a BEB simulation, which models the energy status of the BEB system over the course of the day, including energy consumption and charging. The overarching goal of this model is to smooth the production of the utility's traditional energy sources of coal, natural gas, and nuclear. See Figure 1 below for a flow chart of the simulation.

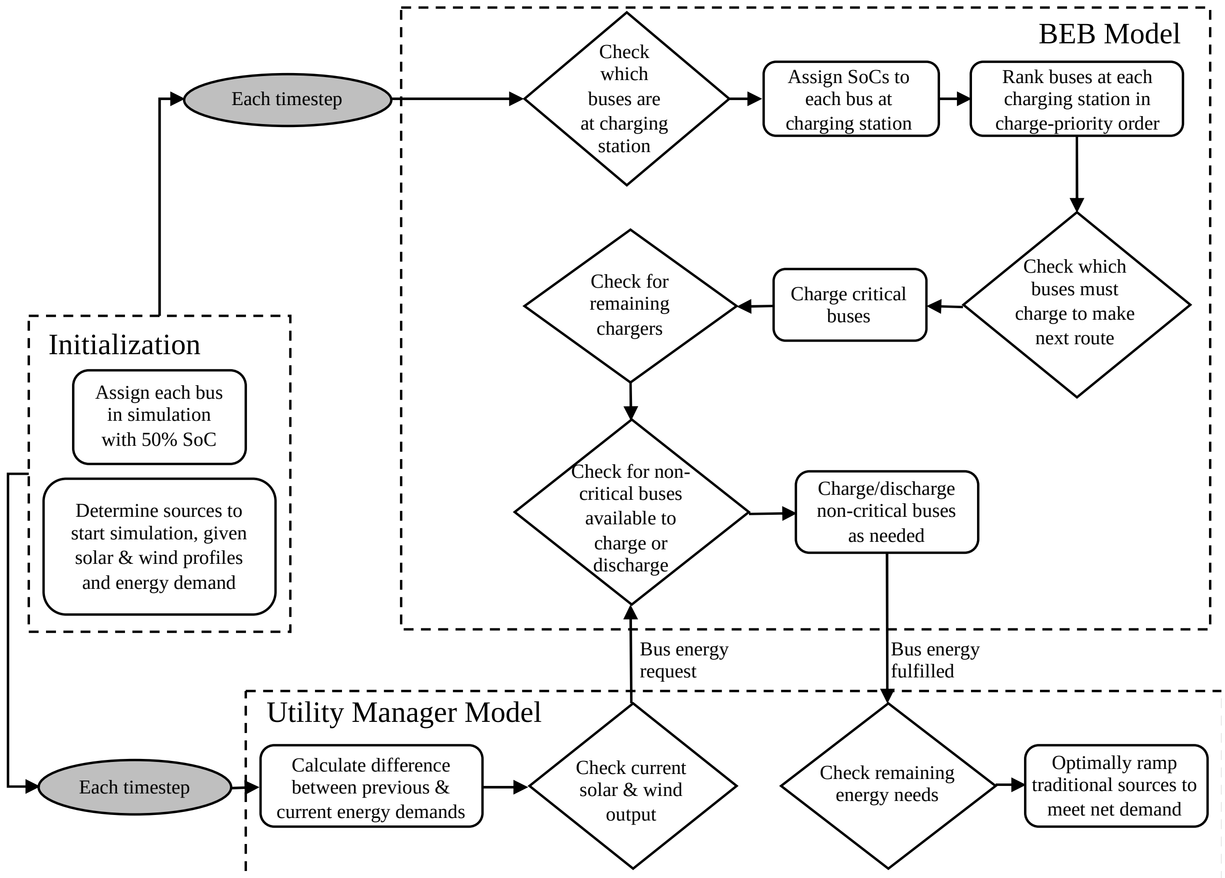

Figure 1 Flowchart of developed simulation model

Utility Manager Simulation Model

This model simulates the energy sources used to meet the demands of the model region. It assumes that the utility manager's sole aim is to minimize cost to meet such energy demands, meaning that GHG emissions or other potential motivations are not considered in this decision-making. The inputs to this model are the energy sources available to the utility manager, and each of those sources' energy type, maximum capacity, minimum running load, variable operating and maintenance (O&M) cost, ramp rate, ramping cost, and startup cost. For the model region, the available energy sources and their maximum capacities are publicly available (Austin Energy B, 2018). These sources consist of coal, simple cycle natural gas (SCNG), combined cycle natural gas (CCNG), steam-powered natural gas, and nuclear plants, as well as wind and solar installations. Operational information for each energy type is shown in Table 1 (U.S. EIA, 2016 and Van Den Bergh & Delarue, 2015).

With the different energy sources as inputs, this model also reads in, at each timestep, solar and wind production, as well as energy demands from the BEB charging, and non-BEB energy demands (Austin Energy A, 2018 and Sargent, 2018). The model assumes that energy sources are always available to run up to the maximum specified capacity, with ramp rates constraining how quickly they can get there.

Table 1 Operational information of different energy sources

Energy Source Type	Variable O&M Cost ($/MWh)	Minimum Load (% nominal/min)	Ramp Rate (% nominal/min)	Ramping Cost ($/ΔMW)	Startup Cost ($/ΔMW)
Coal (steam)	4.33	32.5	2.330	2.227	98.960
SC Natural Gas	4.93	35	12.92	0.9896	52.449
CC Natural Gas	4.93	40	5.415	0.6185	55.665
Natural Gas (steam)	4.93	40	3.415	1.732	90.301
Nuclear	2.30	45	2.625	0	43.295
Wind	0	0	100	0	0
Solar	0	0	100	0	0

The timestep used in this study is one minute and the total model run time is 24 hours. Each timestep, the utility manager determines how much energy is required and the means to provide the energy. As is shown in Eq. (1), at each timestep *t* the total power required from bus and non-bus related loads (MW), D_t, must equal the sum of the power production $P_{i,t}$ (MW) of each energy source *i* that is currently on. $O_{i,t}$ is a binary indicator of energy source *i* being on ($O_{i,t} = 1$) or off ($O_{i,t} = 0$).

$$D_t = \sum_i P_{i,t} * O_{i,t} \tag{1}$$

To determine how to fulfill the power required in each timestep, the utility manager uses the objective function in Eq. (2) subject to constraint Eq. (1) and (3), where C_i is the variable O&M cost of source *i* ($/MW min), RC_i is the ramping cost ($/ΔMW) and SC_i is the startup cost ($/ΔMW), each of energy source *i*.

$$Minimize\{\sum_i \left(O_{i,t}C_iP_{i,t} + \max(0, P_{i,t} - P_{i,t-1}) * RC_i + \max\left(0, O_{i,t} - O_{i,t-1}\right) * Q_{i,min} * SC_i\right)\} \tag{2}$$

$$L_{i,min} \leq P_{i,t} \leq L_{i,max} \text{ for all } i \text{ with } O_{i,t} = 1 \tag{3}$$

$L_{i,max}$ and $L_{i,min}$ are the maximum and minimum power production (MW) that energy source *i* is capable of achieving at the current timestep, constrained by ramp rates and maximum and minimum capacities (Eq. (4) – (7)).

$$L_{i,min} = P_{i,t-1} - R_i \tag{4}$$

$$L_{i,min} \geq Q_{i,min} \tag{5}$$

$$L_{i,max} = P_{i,t-1} + R_i \tag{6}$$

$$L_{i,max} \leq Q_{i,max} \tag{7}$$

where R_i is the maximum change in power (MW) in one minute, $Q_{i,min}$ is the minimum power capacity (MW), and $Q_{i,max}$ is the maximum power capacity (MW), each of energy source *i*. If an energy source was off ($O_{i,t} = 0$) in the previous timestep, then it can produce $Q_{i,min}$ power in the current timestep. Additionally, an energy source can turn off if $L_{i,min} = Q_{i,min}$.

Note that to initialize the model (when $t = 0$), the utility manager does not consider ramp rates or startup costs; it just runs the plants with the lowest variable O&M cost to reach the required production levels at the model start time. This effectively means that, during initialization, constraint Eq. (4) and (6) are not considered and $RC_i = SC_i = 0$.

Each timestep, the model issues a power request to the bus manager. The goal of this power request is to use BEB charging to buffer sharp changes in renewable energy production, allowing for smoother production from traditional energy sources, thereby reducing the utility manager's costs. To develop the power request, the model first uses Eq. (8), which defines G_t, the total renewable energy generation, as the sum of W_t and S_t, the wind and solar production, all at time t in MW.

$$G_t = W_t + S_t \tag{8}$$

The power request, $R_{buses,t}$, is then given in Eq. (9), where $\bar{B}$ is the average bus energy consumption given by Eq. (10) and $\widetilde{G_t}$ is the filtered G_t using a low-pass filter given by Eq. (11), each in MW, where $f = 0.52$ is the filter factor used. This filter factor was optimized to minimize the cost to the utility manager. $\widetilde{G_t}$ is initialized as G_t at $t = 0$, and is updated by Eq. (11) in each subsequent timestep.

$$R_{buses,t} = \bar{B} + G_t - \widetilde{G_t} \tag{9}$$

$$\bar{B} = \frac{1}{t_f - t_i} * \frac{1\,MWh}{1000\,kWh} * \sum_b d_b * c_b \tag{10}$$

$$\widetilde{G_t} = f * \widetilde{G_{t-1}} + (1 - f) * G_t \tag{1}$$

where t_f is the final model timestep, t_i is the initial model timestep, d_b is the total distance traveled by bus b over the course of the day (miles), and c_b is the consumption rate of bus b (kWh/mile).

BEB Simulation Model

This model simulates the BEB system over the course of the day. Three bus types are considered, with all buses' states of charge (SoC) constrained so that they cannot go below 10% or above 90%, to preserve the battery's long-term health, as shown in Eq. (12). There is one charge opportunity defined per route. If the distance between charge opportunities is less than 18 miles, an 80-kWh battery capacity is used, with a consumption rate of 1.69 kWh/mile and a charge rate of 4.17 kWh/min, based on the Proterra Catalyst BEB model. If the distance between charge opportunities is 18 to 37 miles, a 200-kWh battery capacity is used, with a consumption rate of 2.16 kWh/mile and a charge rate of 4.17 kWh/min, based on the New Flyer XE40. Finally, if the distance between charge opportunities is greater than 37 miles, a battery capacity of 324 kWh is used, with a consumption rate of 2.14 kWh/mile and a charge rate of 3.33 kWh/min, based on the BYD 40-Electric. This selection ensures that fully-charged (90% SoC) buses can skip a charge opportunity and still complete their routes. These consumption rates are based on an Altoona Bus Research and Testing Centre report that used an average of different driving cycle types, and charge rates are also averaged (Proterra-E40, 2015; New Flyer, 2015; BYD-40E, 2014).

$$0.1 \leq S_{b,t} \leq 0.9 \text{ for all } t \tag{2}$$

Each 1-minute timestep, the bus manager determines the SoC of each bus in the system and defines which buses are able to charge. If the bus was charging during the previous timestep, the SoC increases by the charge rate r_b (kWh/min), as shown in Eq. (13). If the bus was running during that timestep, then the SoC decreases falls as a function of the consumption rate c_b (kWh/mile) and the average speed traveled during that timestep $v_{b,t}$ (miles/hour), as in Eq. (14). $S_{b,t}$ is the SoC at time t (between 0 and 1).

$$S_{b,t} = r_b * (1 \text{ min}) \tag{3}$$

$$S_{b,t} = c_b * v_{b,t} * \frac{1\,hr}{60\,mins} \tag{4}$$

Of the buses at charge opportunities at each timestep, the manager compiles a normalized priority list to determine the order in which buses should be charged. This list is ordered based on Eq. (15), where a higher value of $p_{b,t}$ (unitless) equates to a higher charging priority for bus b at time *t*. $E_{b,t}$ is the energy needed by bus b for the next route at time *t* (kWh), $T_{b,t}$ is the time until bus b must leave the charger at time *t* (minutes). There are separate priority lists for each charging station and for each charger type. The 80-kWh buses are constrained to charge at EVA080K chargers and the 200- and 324-kWh buses must charge at SAE J3105 chargers, based on bus model specifications.

$$p_{b,t} = \frac{E_{b,t}}{T_{b,t} r_b} \tag{5}$$

When $p_{b,t} = 1$, the bus is deemed in the critical charging category, and must charge during that timestep and all timesteps $T_{b,t}$ until the bus must leave the charger to make its route. Once buses are assigned chargers, they are removed from the priority list for that timestep. After all critical buses are assigned a charger, the bus manager looks at the power request from the utility manager in Eq. (16) to understand what to do next, where $z_{b,t}$ is a binary indicator of bus *b* charging (1) or not (0) at time *t*.

$$X_{buses,t} = R_{buses,t} - \sum_b z_{b,t} r_b \tag{6}$$

If $X_{buses,t}$ is positive, the bus manager aims to charge more buses than just the critical buses. In this case the bus manager looks at the top of the priority list and assigns that bus to a charger if there is a charger available at that bus's charging station and it would not violate the constraint in Eq. (12). If this is the case, Eq. (16) is updated and that bus is removed from the priority list for that timestep. If there is no charger available at that charging station, then the bus does not charge but it is still removed from the priority list for that timestep. The bus manager continues down the list so long as $X_{buses,t}$ is positive, there are still chargers available, and there are still buses that qualify to charge. If any of these are not true, this portion of the model terminates, and the achieved power for that timestep is sent to the utility manager.

In contrast, if $X_{buses,t}$ is negative after all critical buses are assigned a charger, the bus manager tries to discharge some buses. The bus manager starts at the bottom of the priority list and assigns that bus to discharge if there is a charger available at that bus's charging station and if the bus will still have enough energy for its next route after it discharges at rate $-r_b$ for that timestep. If both of these are true and Eq. (12) will not be violated, Eq. (16) is updated and that bus is removed from the priority list at that timestep. If those conditions to discharge are not true, that bus does not discharge, and it is removed from the priority list for that timestep. The bus manager continues up the list so long as $X_{buses,t}$ is negative, there are still chargers available, and there are still buses that qualify to discharge. If any of these are not true, this portion of the model terminates, and the achieved power is sent to the utility manager.

Cost Analysis

A cost analysis is completed for each model run. Bus capital and operating costs, utility operating costs, and GHG external costs are considered. Utility operating costs are detailed in Table 1.

Table 2 Cost assumptions for scenario cost analysis

Bus capital and infrastructure costs (USD)	
Cost of new diesel bus ($/bus)	$280,000
Cost of new 80-kWh BEB bus ($/bus)	$491,000
Cost of new 200-kWh BEB bus ($/bus)	$553,000
Cost of new 324-kWh BEB bus ($/bus)	$700,000
Cost of 80-kWh BEB charger ($/charger outlet)	0*
Cost of 200-kWh BEB charger ($/charger outlet)	$250,000
Cost of 324-kWh BEB charger ($/charger outlet)	$250,000
Bus operating assumptions and costs	
Diesel bus fuel mileage (MPG)	4.2
80-kWh BEB energy consumption (kWh/mile)	1.69
200-kWh BEB energy consumption (kWh/mile)	2.16
324-kWh BEB energy consumption (kWh/mile)	2.14
Diesel fuel cost ($/gallon)	$2.50
Electricity cost ($/kWh)[2]	$0.06**
Diesel bus operating cost ($/mile)	$0.48
80-kWh BEB operating cost ($/mile)	$0.10
200-kWh BEB operating cost ($/mile)	$0.13
324-kWh BEB operating cost ($/mile)	$0.13
GHG emission assumptions and costs	
Diesel CO_2 emissions (lbs/mile)	3.85
Diesel NO_X emissions (lbs/mile)	4.84×10^{-4}
Diesel SO_2 emissions (lbs/mile)	2.38×10^{-4}
Diesel PM emissions (lbs/mile)	1.10×10^{-3}
Coal power plant CO_2 emissions (lbs/kWh)	0.703
Coal power plant NO_X emissions (lbs/kWh)	2.05×10^{-4}
Coal power plant SO_2 emissions (lbs/kWh)	3.41×10^{-4}
Coal power plant PM emissions (lbs/kWh)	1.40×10^{-4}
Natural gas (CC) power plant CO_2 emissions (lbs/kWh)	0.399
Natural gas (CC) power plant NO_X emissions (lbs/kWh)	2.56×10^{-5}
Natural gas (CC) power plant SO_2 emissions (lbs/kWh)	3.41×10^{-6}
Natural gas (CC) power plant PM emissions (lbs/kWh)	1.92×10^{-7}
Natural gas (SC) power plant CO_2 emissions (lbs/kWh)	0.399
Natural gas (SC) power plant NO_X emissions (lbs/kWh)	1.02×10^{-4}
Natural gas (SC) power plant SO_2 emissions (lbs/kWh)	3.41×10^{-6}
Natural gas (SC) power plant PM emissions (lbs/kWh)	5.52×10^{-7}
Total cost of CO_2 ($/lb)	$0.06
Total cost of NO_X ($/lb)	$1.40
Total cost of SO_2 ($/lb)	$1.00
Total cost of PM (< 10 μm) ($/lb)	$2.15

*One charger is provided with each BYD 40-Electric bus, included in the cost of the bus.
**Assuming Austin's industrial-rated electricity cost.
Sources for this table: Austin Energy, 2018 B; Biswas et. al., 2009; BYD, 2015; Carpenter, 2017; Green Car Congress, 2014; IER, 2009; Kane, 2016; Matthews et. al., 2001; Mitchell, 2017; Muncrief, 2016; NREL, 2016; Proterra, 2016; Proterra, 2017; Proterra, 2018 A; Proterra, 2018 B; Proterra, 2019; Reuters, 2010; U.S. EIA, 2016; van den Bergh & Botzen, 2015; Yasar et. al., 2013.

The bus-related assumptions and costs are based on four different buses currently on the market: a standard 40 diesel bus, the 324-kWh Proterra Catalyst, the 200-kWh NewFlyer XE40, and the 80-kWh BYD 40-Electric. For GHG external costs, many estimates exist. These estimates are challenging due to many factors of uncertainty. Averages of several estimates are used in this analysis. Nuclear, wind, and solar are assumed to produce zero emissions. See Table 2 for more details.

CASE STUDY

Input Data

The Austin, Texas region is used to test the methodology outlined in the previous section. The Austin bus fleet currently consists of 423 buses. There are eighty-one bus routes of varying lengths. General Transit Feed Specification (GTFS) data was used to define route schedules to be used as input to the BEB Simulation model (CapMetro, 2019). Thirteen charging station locations were defined across the Austin region and each bus route has one charging location defined on its route.

In addition to solar and wind power purchases, Austin's electricity comes from two coal plants each with capacities of 285 MW, two nuclear plants with capacities of 200 MW, and fourteen natural gas plants of varying capacities between 48 and 435 MW. The capacity factor of Austin's nuclear plants is 100.12% on average, and it is 78.00% for coal and 16.57% for natural gas (Austin Energy B, 2018). It is clear that Austin runs its coal and nuclear plants much more constantly than its natural gas plants, which might be attributed to the operational costs of each, shown in Table 1. Each plant's capacity rating is read in at the beginning of the model run and is matched with ramp rates and operational costs from Table 1 based on their fuel source.

One example of a solar and wind energy profile is tested in this case study. A standard idealized solar profile was approximated, centered at 2 pm, where it reaches its maximum capacity, and going to zero at sunset and sunrise. Real wind data from the Electricity Reliability Council of Texas (ERCOT) region was used, scaled to match Austin's capacity (ERCOT, 2019). Often times, wind production valleys align with solar production peaks, as happens in this example. It is an ideal situation from the utility manager's perspective because it means less ramping of traditional energy sources of coal and natural gas, which is costly and emitting. It is possible that wind and solar peaking can occur more simultaneously, which has the possibility of major traditional ramping implications, so this case should be tested in the future.

Finally, a simplified non-BEB energy consumption profile was assumed based on average daily energy consumption in the city of Austin in 2018, fit to a standard energy consumption model (Austin Energy A, 2018 and Sargent, 2018). This was assumed to be the base energy demand, with additional loads coming from BEB charging. Note that the selected solar and wind production profiles made up 39.1% of the required energy needed for the non-bus consumption. This is close to the average of 37.5% mentioned previously, and thus these profiles were deemed reasonable for a typical day in Austin. See Figure 2 below for these consumption and production profiles.

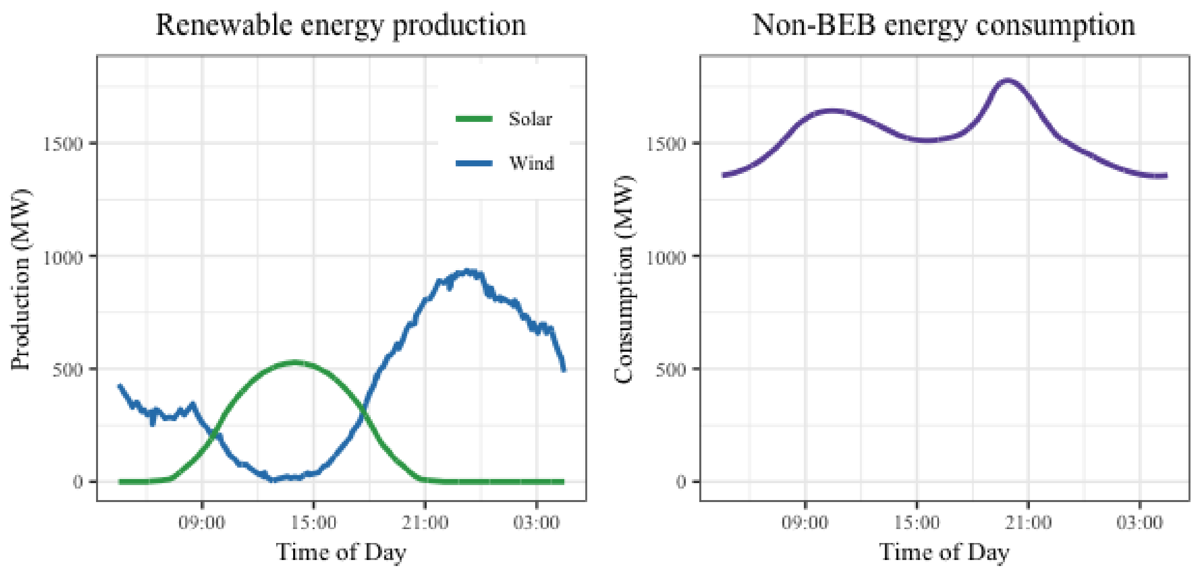

Figure 2 Solar and wind production and non-bus electricity consumption tested

Scenario Definition

Three scenarios are considered in this study. In each scenario, bus routes run the same schedule. In addition, the same non-BEB energy consumption is used. The first scenario is meant to reflect the current state in Austin where all buses are diesel. The second scenario is a non-smart-charging (non-SC) BEB scenario, where the bus manager does not receive feedback from the utility manager. At each timestep in the non-SC scenario, buses with the highest charge priorities are assigned to chargers (Eq. (12)-(15)). Finally, the third scenario is a smart charging (SC) BEB scenario. This scenario charges based on Eq. (12)-(16), where buses aim to match power requests made by the utility manager at each timestep.

For the BEB scenarios, the number of chargers was not optimized, but several iterations were tested to determine the minimum number of chargers at each location where buses could always make their routes. In addition, bus chargers come in pairs, so an even number of chargers was required at each location. Also, because the 80-kWh buses include a charger with their purchase, those chargers did not need to be minimized.

Buses are assumed to last twelve years. We assume that there is the same number of inactive buses in the fleet in the diesel and BEB cases, though there are more active buses in the BEB scenarios because of additional time needed to charge. This is likely a conservative assumption because there is significantly less maintenance needed on BEBs than diesel buses (due to fewer moving parts in EVs). The lifetime of charging stations is generally listed as 30 years. However, because this is a new technology, they are likely to be obsolete before then. Therefore, we assume that the lifetime of chargers is 12 years to accommodate the expected technological advancements in that time. We also assume that the bus manager would not be motivated to run the SC scenario, which helps the utility manager, unless they were given a discount on charging costs. We assumed they were given a 50% discount on electricity in the SC scenario. This seems like a steep discount, but the Results section will show that this discount more than pays for itself from the utility manager's perspective.

RESULTS

A comparative analysis is performed for all scenarios based on cost and GHG emissions, shown in Table 3. Annual cost to the bus manager includes bus purchase, fueling, and infrastructure cost. Annual variable cost to the utility manager includes their variable O&M, startup, and ramping costs. It assumes each day is like the day detailed in Figure 2 which is a limitation, though the renewable production is fairly representative of an average day in Austin. In the SC scenario, the bus electricity discount is also included in the utility manager's cost.

Table 3 Summary of scenario results

	Current State	Non-SC BEB	SC BEB
Bus statistics and costs			
Number of daily active buses in the fleet	302	423	423
Total number of buses in the fleet	423	544	544
Average cost of buses in fleet	\$280,000	\$646,253	\$646,253
Daily total diesel consumed (gallons)	21,080	0	0
Daily total net bus charging (MWh)	N/A	188.36	188.36
Total daily fueling/charging cost	\$52,699	\$11,370	\$5,685
Infrastructure statistics and costs			
Number of EVA080K chargers	0	38	38
Number of SAE J3105 chargers needed	0	92	92
Annual charging infrastructure costs	0	\$1.92M	\$1.92M
Total energy production statistics and cost			
Total daily electric energy production (MWh)	36,760	36,940	36,940
Daily coal energy production (MWh & % of total)	10.2.k (27.8%)	10.2k (27.5%)	9.01k (24.4%)
Daily gas energy production (MWh & % of total)	2.71k (7.37%)	2.93k (7.94%)	4.53k (12.3%)
Daily nuclear energy production (MWh & % of total)	9.49k (25.8%)	9.47k (25.6%)	9.03k (24.4%)
Daily wind energy production (MWh & % of total)	10.2k (27.7%)	10.2k (27.6%)	10.2k (27.6%)
Daily solar energy production (MWh & % of total)	4.17k (11.4%)	4.17k (11.3%)	4.17k (11.3%)
Daily cost of production	\$1.09M	\$1.09M	\$845k
Electricity grid and bus greenhouse gas emissions and costs			
Total daily CO_2 emissions (tons)	4,308	4,160	4,072
Total daily NO_X emissions (tons)	1.205	1.191	1.035
Total daily SO_2 emissions (tons)	1.756	1.740	1.546
Total daily PM emissions (tons)	0.7637	0.7128	0.6313
Daily external cost of CO_2 emissions	\$538,500	\$520,000	\$509,000
Daily external cost of NO_X emissions	\$3,373	\$3,336	\$2,899
Daily external cost of SO_2 emissions	\$3,512	\$3,480	\$3,089
Daily external cost of PM emissions	\$3,284	\$3,065	\$2,715
Summary of costs and savings			
Annual cost to the bus manager	\$29.1M	\$35.4M	\$32.3 M
Annual variable cost to utility manager	\$398M	\$396M	\$312M
Annual external cost of emissions	\$200M	\$193M	\$189M
Overall annual net benefit relative to current state	N/A	\$2.60M	\$94.6M

The capital cost for BEBs is more than twice that of diesel buses. However, the daily fueling cost is 4.6 times lower for BEBs because of the lower cost of electricity compared to diesel. Given this, the annual bus manager's cost of owning a BEB fleet, which is larger than the diesel fleet, is only \$6.3M more in the non-SC scenario and is \$3.2M more in the SC scenario. This annual cost assumes the buses and charging station costs are distributed over 12 years and does not include any interest payments.

Of course, total electricity consumption increases slightly in both BEB scenarios relative to the current state. However, the utility cost in the SC scenario decreases by nearly 22% compared to the current state. This shows why the utility manager would be motivated to provide a major discount to the bus manager for participating in V2G smart-charging. The utility manager saves approximately \$84M annually in the SC scenario compared to the other two scenarios, which is our most significant model result.

Finally, since diesel is much more emitting per-unit energy than any power plant type, the total social cost of emissions decreases significantly in both BEB scenarios compared to the current state, with slightly lower emissions in the SC scenario compared to the non-SC scenario because there is less coal and more natural gas production. Note that this study only considers emissions from the electricity grid and the buses. It does not consider emissions from other forms of transportation or other sources, but it is assumed that those are constant across scenarios.

The top pane of Figure 3 shows the total production by energy source in the non-SC scenario. In this scenario, nuclear runs constant at full capacity until wind generation increases at night. Both coal plants also run at full capacity until about 1 pm, when solar production nears maximum capacity, and one of the coal plants dips in production. Then around 9 pm when base load energy demands decrease and wind becomes strong, both coal plants dip to their minimum capacity. The SCNG plants are more variable because these are considered "peaker" plants. They are smaller plants that can ramp quickly, so they can respond to sharp changes in production needs. Note that CCNG does not run in this scenario.

In the bottom pane of Figure 3, the change in production by source is shown for SC relative to the non-SC scenario, where positive values indicate that the SC scenario produces more, and negative values indicate that the SC scenario produces less than the non-SC scenario. In the SC scenario, nuclear ramps down a bit more around 9pm than the non-SC scenario. There are also slight differences in coal production. However, what is most noteworthy in this scenario is that instead of running many SCNG "peaker" plants, the utility runs its CCNG plant. CCNG plants have lower ramp rates, but they are cheaper to ramp, so the utility prefers them. Because the SC scenario smooths the renewable production, the utility is able to substitute the emitting, costly, quick-ramping SCNG plants for the more efficient CCNG plant.

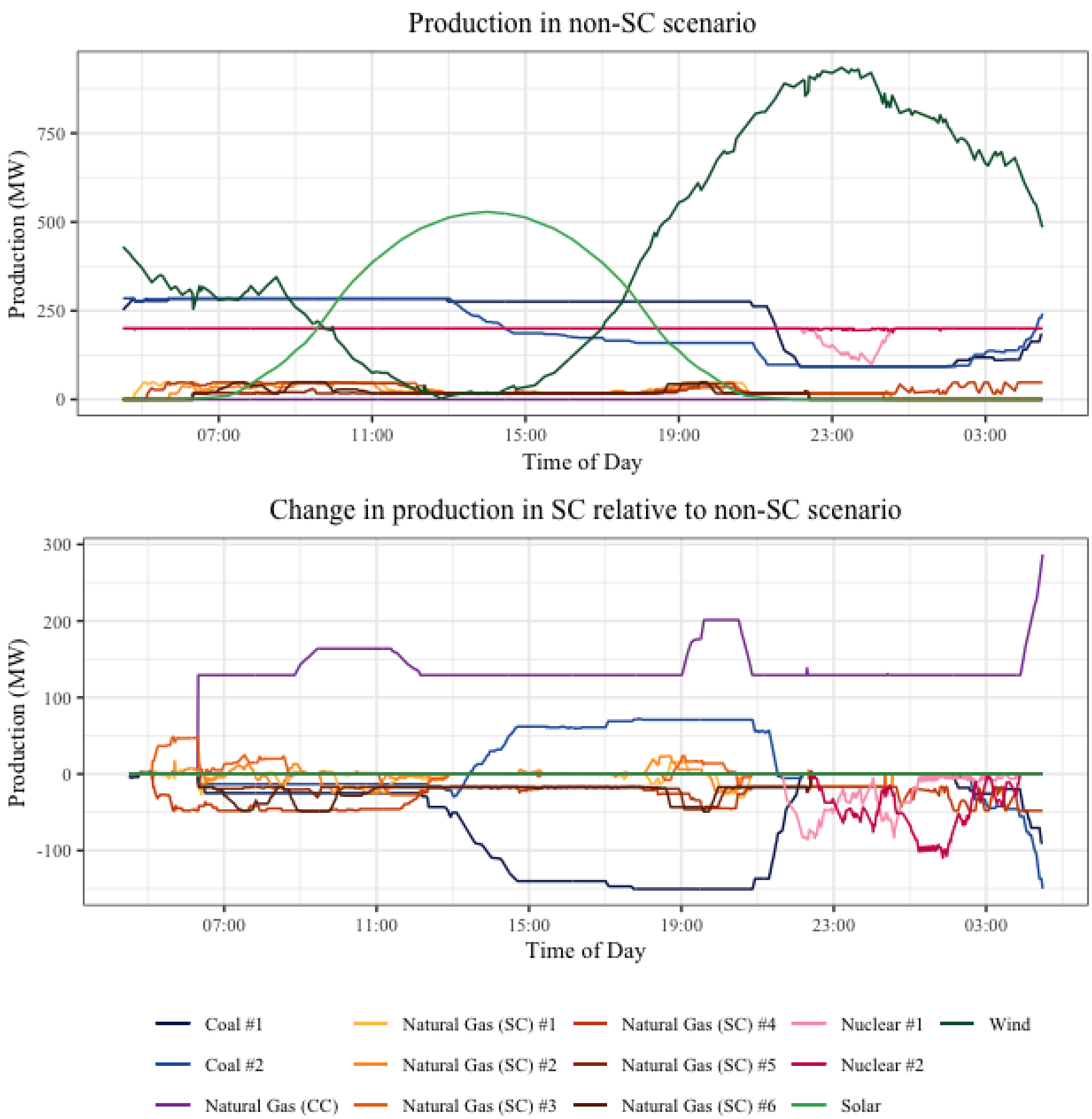

Figure 3 Production by source in non-SC scenario and change in production in SC relative to non-SC scenario

Recall that in the non-SC scenario, the bus manager receives no feedback from the utility manager and buses charge on a priority-basis. In the SC scenario, BEBs responds to power requests from the utility manager to smooth sharp changes in renewable energy production, mainly from wind production in this case study. In Figure 4 the power requested is plotted along with the actual power achieved by the bus manager. The bus manager is not always able to fully meet the power requests, but it does quite well given that buses must be sufficiently charged to make their routes and must remain within SoC limits of 10% to 90%. Figure 5 shows the difference in the net BEB system electricity consumption in the non-SC and SC scenarios. The SC scenario looks much noisier because it is attempting to smooth noise from renewable energy production.

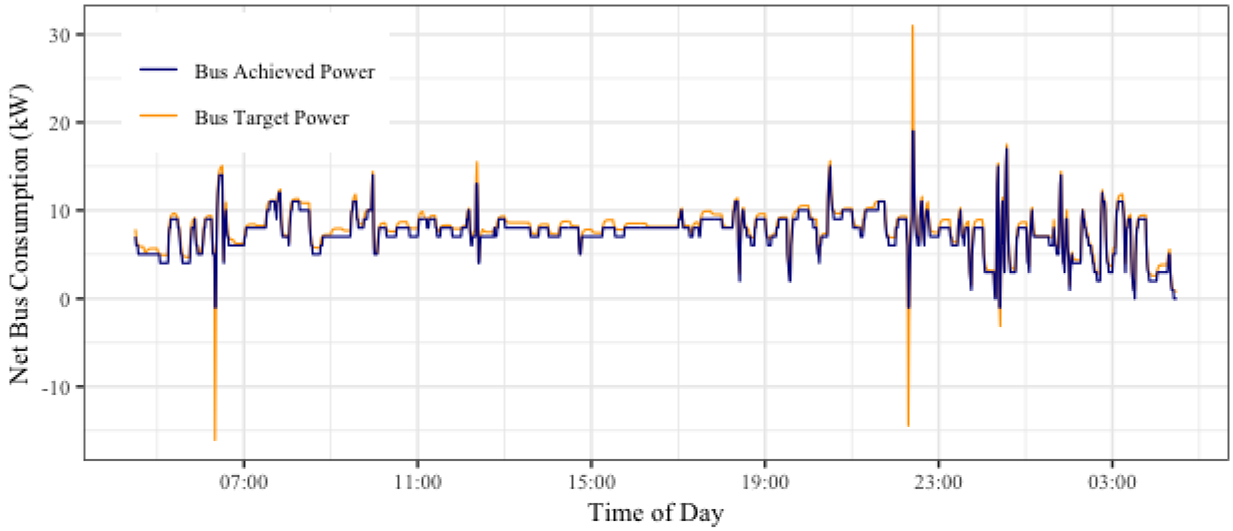

Figure 4 BEB system target vs. achieved consumption (from Eq. 9 & 16)

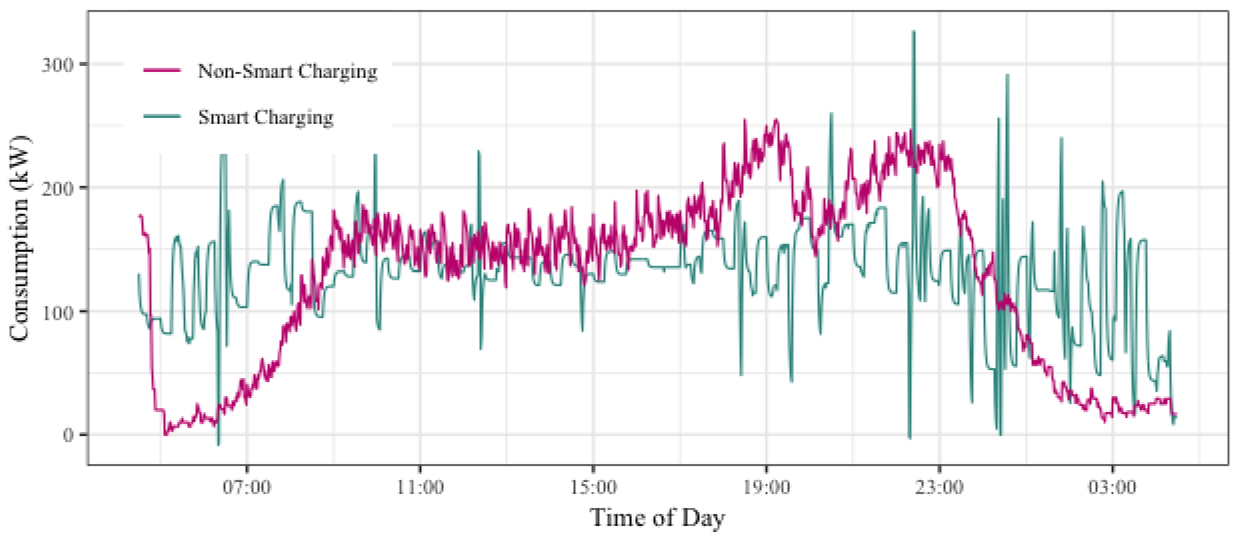

Figure 5 Net BEB system energy consumption in non-SC and SC scenarios

CONCLUSIONS

This study finds that BEB annualized costs are more expensive than those of diesel buses from a transit agency's cost perspective, though it is not insurmountable. These costs could be offset by renewable energy or low-emission incentives, if carbon taxing, electric bus incentives, or other similar legislature is passed in the future. From the utility manager's perspective, the prospect is very encouraging. If Austin fully electrified its bus fleet and participated in V2G SC strategies, there is the possibility of substantial cost savings for the utility manager, even if they significantly reduce the cost of electricity for buses. When the BEBs in this case study charged according to our proposed SC model, the fleet manager was able to cut nearly 22% of their daily cost.

When considering the social costs of bus emissions, BEBs are more attractive yet. With Austin, and many other cities, planning to expand energy generation from solar and wind, this switch in transit technologies will only become more beneficial to human health. Simply electrifying Austin's buses, without any SC strategies, the total external cost of the considered emissions falls by approximately 3.42%, and with SC strategies the cost of emissions falls by 5.64%. This is significant given that this is only considering the electrification of diesel buses. It is worth noting that our results may have underestimated emissions from the utility across all scenarios because only the emissions per MWh of each source were considered. It is intuitive that ramping and starting up plants would be less efficient than running a constant load, thus creating more GHG emissions. We could confidently argue that if we included this cost in the future, the SC scenario would look even more positive due to less ramping.

Finally, all costs considered, both BEB scenarios are preferable compared to the current state diesel scenario. The non-SC scenario is $2.6M net positive (0.41% savings relative to current state) and the SC scenario is $94.6M net positive annually (15.1% savings relative to current state).

The focus of this study was to develop a Smart Charging framework that could be used to increase the practicality of heavily-renewable-dependent electricity grids by using electrified transportation as a buffer to the grid. Our case study applied this framework to the Austin bus transit fleet, which is limited in capability and scope. This framework could be applied to a wider range of electrified systems including school buses, trash and recycling trucks, mail delivery trucks, and even personal EVs and other forms of battery storage systems. If more electrified systems are included in this analysis in the future, the response to fluctuations in renewable generation could be even more effective. In addition, with this increase in capacity, the methodology could go further in using electrified transportation systems to counteract daily cyclic power differences as well.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: T. Wellik, J. Griffin, M. Mohamed; data collection: T. Wellik; analysis and interpretation of results: T. Wellik, J. Griffin; draft manuscript preparation: T. Wellik, K. Kockelman. All authors reviewed the results and approved the final version of the manuscript.

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