

# A Continuous Approach to Minimize Cost for Charging Electric Bus Fleets

Daniel Mortensen, Jacob Gunther, Greg Droge, Alexander Brown, Justin Whitaker

*Abstract—*

**Index Terms—**Battery Electric Buses, Cost Minimization, Multi-Rate Charging, Mixed Integer Linear Program

## I. INTRODUCTION

Battery powered electric motors for buses have long been a desired alternative to the internal combustion engine [18]. The reduced maintenance [1], zero emissions [15], and access to renewable energy [7] are but some of the benefits that have caused transit authorities to begin incorporating them into their bus fleets.

Despite their benefits, transitioning to battery electric buses (BEBs) must address additional challenges, in particular, their extended refuel times. If a diesel or CNG bus runs low on fuel, refueling takes five to ten minutes. An electric bus on the other hand may require several hours, causing the bus to fall behind schedule.

Maintaining a schedule while staying charged is one of the main challenges that BEBs face, and requires careful planning which must account for the battery discharge along routes, charge times, and a limited number of chargers.

Charging while a bus is in motion, or dynamic charging, is one way to simplify a charge plan. There are a number of ways to do this including overhead [8] and inductive charging [14] [4]. An overhead charging scenario allows the bus to charge on overhead power lines while in motion while inductive charging relies on specialized hardware in the roads to inductively transfer energy when a bus passes overhead. Both methods remove the need to stop for service and allow an electrical vehicle to stay in service indefinitely. They also require extensive infrastructure [2] that may not be available.

In the absence of infrastructure, [13] and [30] have proposed methods that exchange depleted batteries for fresh ones. Such a method would eliminate both the logistical challenges of planning and the infrastructure dependence of dynamic charging. The only drawback, is that BEBs are not built with battery exchanges in mind, therefore the task can require specialized hardware, technical expertise, or automation, all of which add complexity and cost.

One charge option that avoids both the infrastructural demands of dynamic charging and the technical difficulties of battery swapping is stationary charging, which plans rest periods into a bus's schedule during which that bus can charge [29]. Stationary charging is the least invasive form of bus charging because it only requires charging hardware at

specific locations and makes no exchanges to bus batteries. Prior work in this area addresses a number of problems including distributed charging networks [20], bus availability, environmental impact [31], route scheduling [24], battery health [12], the cost of electricity [16] and the cost of charging infrastructure [28].

One drawback to using a stationary charging solution is that it does require significant rest periods for charging. One way to decrease the charge intervals is to use high power chargers, which deliver more energy in a smaller period of time. Large power demands however do increase the overall cost of energy because they must be supported by highly capable infrastructure [26], [9], [5]. An effective charge plan must therefore balance the need to charge quickly with the desire to maintain a low power profile [7], [21], [23], [3], [27], [11] which includes power used by BEBs and the power needed by other consumers.

Because the additional power users are outside the control of the charge plan, their power requirements are referred to in this paper as “uncontrolled loads”. Uncontrolled loads complicate the problem of finding an optimal charge plan. If a bus charges in the presence of a large uncontrolled load, the overall power profile rises, increasing cost for energy.

A significant contribution of [19] was how the authors minimized the the financial impact of charging in the presence of uncontrolled loads by formulating the charge problem as a network flow on a graph and solving for the optimal path through the graph. The graph-based approach represented time discretely, which lent itself well to integrating uncontrolled loads, which are sampled discretely in practice.

Unfortunately, more temporal precision decreases the time step between sections in the graph, which leads to a larger graph and significantly increases the computational complexity. The authors of [6] compute the charge schedule continuously by formulating the charge problem as a bin packing problem [17], yielding a precise time schedule for charging, but finding a continuous-time schedule that incorporates uncontrolled loads and minimizes a comprehensive cost function remains an open problem and is the focus of this paper.

The rest of this paper is organized as follows: Section II discusses the basic problem formulation, Section III discusses linear constraints that govern the behavior and limitations of the rate of charge. Section IV discusses how to incorporate uncontrolled loads into the optimization framework. Section V explains how the objective function is formed, and Section VI discusses performance.

## II. BUS AVAILABILITY AND RESOURCE CONTENTION

The charge scheduling framework described in this paper is formulated as a constrained optimization problem that can be solved as a Mixed Integer Linear Program (MILP) of the form

$$\begin{aligned} \min \mathbf{y}^T \mathbf{v} \text{ subject to} \\ \mathbf{\tilde{A}}\mathbf{y} = \mathbf{\tilde{b}}, \mathbf{A}\mathbf{y} \leq \mathbf{b}, \end{aligned} \quad (1)$$

where  $\mathbf{y}$ ,  $\mathbf{\tilde{A}}$ ,  $\mathbf{A}$ , and  $\mathbf{v}$  represent the solution vector, equality and inequality constraints, and cost vector respectively. In this paper,  $\mathbf{y}$  is comprised of several variables, and is expressed as

$$\mathbf{y} = \begin{bmatrix} \sigma \\ \mathbf{c} \\ \mathbf{s} \\ \mathbf{h} \\ \mathbf{k} \\ \mathbf{r} \\ \mathbf{g} \\ \mathbf{p} \\ q_{\text{on}} \\ q_{\text{all}} \end{bmatrix}, \quad (2)$$

where  $\sigma$  describes on which charger a bus will charge,  $\mathbf{c}$  and  $\mathbf{s}$  describe time intervals over which buses charge,  $\mathbf{h}$  gives the bus state of charge,  $\mathbf{k}$ ,  $\mathbf{r}$  and  $\mathbf{p}$  are used to discretize the effects from  $\mathbf{c}$  and  $\mathbf{s}$ ,  $q_{\text{on}}$  and  $q_{\text{all}}$  represent maximum average power values that are used to compute the monthly cost of power, and  $\mathbf{g}$  is a slack variable for converting the effects of charging from continuous time to discrete intervals.

The cost function in (1) will be designed to model a realistic billing structure used by [22] and minimises the cost in the presence of uncontrolled loads. Additionally, the constraints are designed to incorporate bus schedules, limit bus state of charges, and include a linear charge model calibrated on data from the Utah Transit Authority.

### A. Setup

A solution to the bus charge problem includes both temporal and categorical information. The temporal aspect shows when and for how long a bus should charge, and is represented from left to right. The categorical axis represents each category as a bus and shows which bus must charge as shown in Fig. 1.

Each bus follows a schedule of arrival and departure times, where the  $i^{\text{th}}$  bus's  $j^{\text{th}}$  stop begins at arrival time  $a_{ij}$  and terminates at departure time  $d_{ij}$  (see Fig. 2). A bus can be assigned to charge anytime the bus is in the station such that the charge start time,  $c_{ij}$ , is greater than or equal to  $a_{ij}$ , and the charge stop time,  $s_{ij}$ , is less than the departure time  $d_{ij}$  as shown in Fig. 2. In the context of a MILP, the arrival and departure times  $a_{ij}$  and  $d_{ij}$  are known ahead of time and charge times  $c_{ij}$  and  $s_{ij}$  are optimization variables.

### B. Constraints

The relationship between the arrival, departure, and charge intervals for the  $i^{\text{th}}$  bus at the  $j^{\text{th}}$  stop can be expressed as a set of inequality constraints such that

$$\begin{aligned} a_{ij} &\leq c_{ij} \\ c_{ij} &\leq s_{ij} \\ s_{ij} &\leq d_{ij}. \end{aligned} \quad (3)$$

These constraints can be rewritten such that the optimization variables are on the left, the known parameters are on the right, and the relationship is "less than" (or standard form) such that

$$\begin{aligned} -c_{ij} &\leq -a_{ij} \\ c_{ij} - s_{ij} &\leq 0 \\ s_{ij} &\leq d_{ij}. \end{aligned} \quad (4)$$

Standard form is preferred because it is required by most solvers. Having the optimization variables on the left also allows the expression to be written using matrix notation as

$$\begin{bmatrix} -1 & 0 \\ 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} c_{ij} \\ s_{ij} \end{bmatrix} \leq \begin{bmatrix} -a_{ij} \\ 0 \\ d_{ij} \end{bmatrix}. \quad (5)$$

However, because all constraints must follow the form  $\mathbf{A}\mathbf{y} = \mathbf{b}$  as shown in (1), (5) is expressed in terms of  $\mathbf{y}$  such that

$$\begin{bmatrix} -1_{ij}^c & 0 & \dots & 0 \\ 1_{ij}^c & 0 & \dots & -1_{ij}^d \\ 0 & 0 & \dots & 1_{ij}^d \end{bmatrix} \mathbf{y} \leq \begin{bmatrix} -a_{ij} \\ 0 \\ d_{ij} \end{bmatrix} \quad \forall i, j \quad (6)$$

$$\mathbf{A}_1 \mathbf{y} \leq \mathbf{b}_1,$$

where  $1_{ij}^c$  is 1 at the index that corresponds to  $c_{ij}$ ,  $1_{ij}^d$  is 1 at the index corresponding to  $d_{ij}$ , and  $\mathbf{A}_1$  and  $\mathbf{b}_1$  stack the constraints given in (5) for all  $i, j$ .

The decision variables  $s_{ij}$  and  $c_{ij}$  from (5) show when a bus must start and finish charging, but do not indicate on which charger. The variable  $\sigma$  from (2) is a vector of binary variables. Each element of  $\sigma$  is denoted  $\sigma_{ijk}$  and is 1 when bus  $i$  charges during the  $j^{\text{th}}$  stop at charger  $k$ . Because a bus can only charge at one charger at a time, the values in  $\sigma$  must be constrained such that

$$\sum_k \sigma_{ijk} \leq 1 \quad \forall i, j \quad (7)$$

or in standard form as

$$\begin{bmatrix} 1_{ij1} & 0 & \dots & 0 & 1_{ijk} & \dots \end{bmatrix} \mathbf{y} \leq \mathbf{1} \quad \forall i, j \quad (8)$$

$$\mathbf{A}_2 \mathbf{y} \leq \mathbf{b}_2,$$

where  $1_{ijk}$  represents a 1 at the location corresponding to  $\sigma_{ijk}$ . The variable  $\sigma_{ijk}$  is used in several scenarios. The first is to ensure that buses without charge assignments have a charge

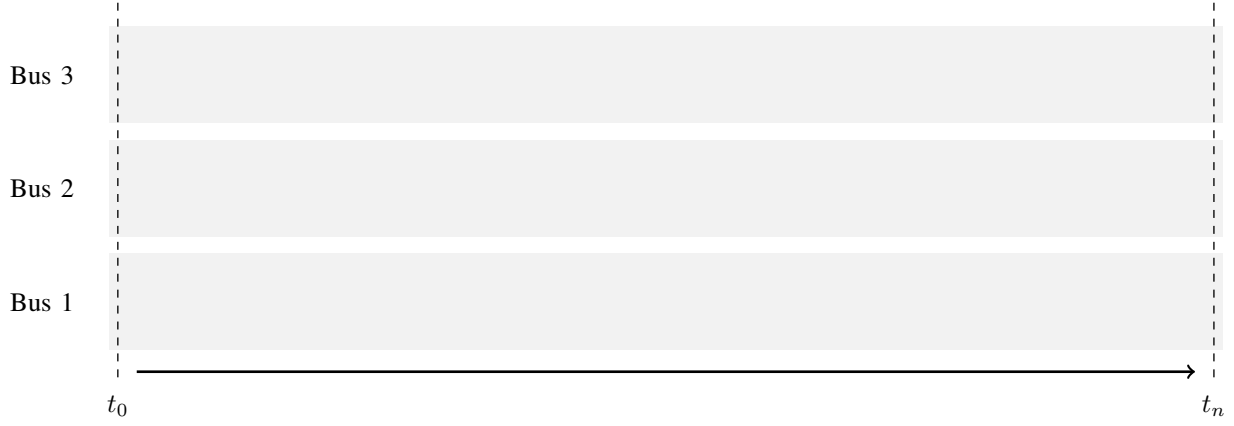


Fig. 1: Description of the bus and time axis

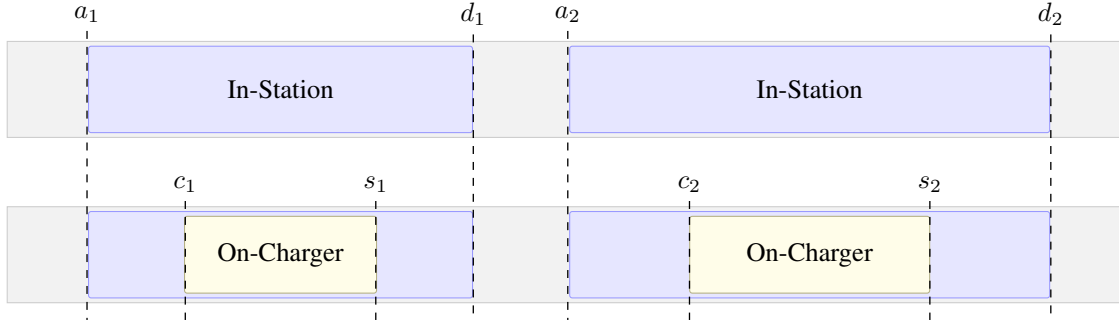


Fig. 2: Bus Charging

time of zero by constraining  $s_{ij}$  and  $c_{ij}$  to be the same value. This is done by letting

$$s_{ij} - c_{ij} \leq M \sum_k \sigma_{ijk} \quad (9)$$

$$s_{ij} - c_{ij} - \sum_k \sigma_{ijk} M \leq 0$$

$$\begin{bmatrix} 1_s & -1_c & -M_{\sigma_1} & \dots & -M_{\sigma_k} \end{bmatrix} \begin{bmatrix} s_{ij} \\ c_{ij} \\ \sigma_{ij1} \\ \vdots \\ \sigma_{ijk} \end{bmatrix} \leq 0 \quad \forall i, j$$

where  $M$  is the maximum difference between  $s_{ij}$  and  $c_{ij}$ , or the number of seconds in a day, also referred to as  $nTime$ , and  $M_{\sigma}$  represents multiple values of  $M$  at locations corresponding to each  $\sigma_{ijk}$ . The constraints in (9) can be appropriately zero padded and stacked for all  $i, j$  to form the linear expression

$$A_3 y \leq b_3 \quad (10)$$

The values in  $\sigma$ ,  $c$ , and  $s$  form a complete charge plan representation where  $c_{ij}$  and  $s_{ij}$  describe time periods when a bus will charge and  $\sigma_{ijk}$  gives which charger to use. (see Fig. 3). The variable  $\sigma_{ijk}$  is also necessary to eliminate situations where more than one bus is assigned to the same charger at the same time. Note that two buses, bus  $i$  and bus  $i'$ , can only be assigned to the same charger at the same time when

for bus  $i$  is less than  $d_{i'j'}$  for bus  $i'$  as shown in Fig. 4. Let  $\mathcal{S}$  be the set of all bus-stop pairs such that  $((i, j), (i', j')) \in \mathcal{S}$  if overlap is possible between bus  $i$  and bus  $i'$  during the  $j$  and  $j'$  stops respectively. Charging overlap can be avoided by constraining

$$\begin{aligned} & c_{i'j'} > s_{ij} \\ & \text{or} \\ & c_{ij} > s_{i'j'} \end{aligned} \quad \forall (ij, i'j') \in \mathcal{S} \quad (11)$$

Let  $l_{(ij, i'j')}$  be a binary decision variable that is 1 when  $c_{i'j'} > s_{ij}$ , and 0 when  $c_{ij} > s_{i'j'}$ . The expression from (11) can be rewritten as

$$\begin{aligned} c_{i'j'} - s_{ij} & > -M l_{(ij, i'j')} \\ c_{ij} - s_{i'j'} & > -M(1 - l_{(ij, i'j')}) \end{aligned} \quad (12)$$

However, this constraint is only necessary when buses  $i$  and  $i'$  must use the same charger. This can be remedied as

$$\begin{aligned} c_{i'j'} - s_{ij} & > M \left[ (\sigma_{i'j'k} + \sigma_{ijk}) - 2 \right] - M l_{(ij, i'j')} \quad \forall k \\ c_{ij} - s_{i'j'} & > M \left[ (\sigma_{i'j'k} + \sigma_{ijk}) - 2 \right] - M(1 - l_{(ij, i'j')}) \quad \forall k \end{aligned} \quad (13)$$

When  $(\sigma_{i'j'k} + \sigma_{ijk}) < 2$ , (13) is trivially satisfied for all values of  $c_{i'j'}$  and  $s_{ij}$ . When  $\sigma_{i'j'k} = \sigma_{ijk} = 1$ , (13)

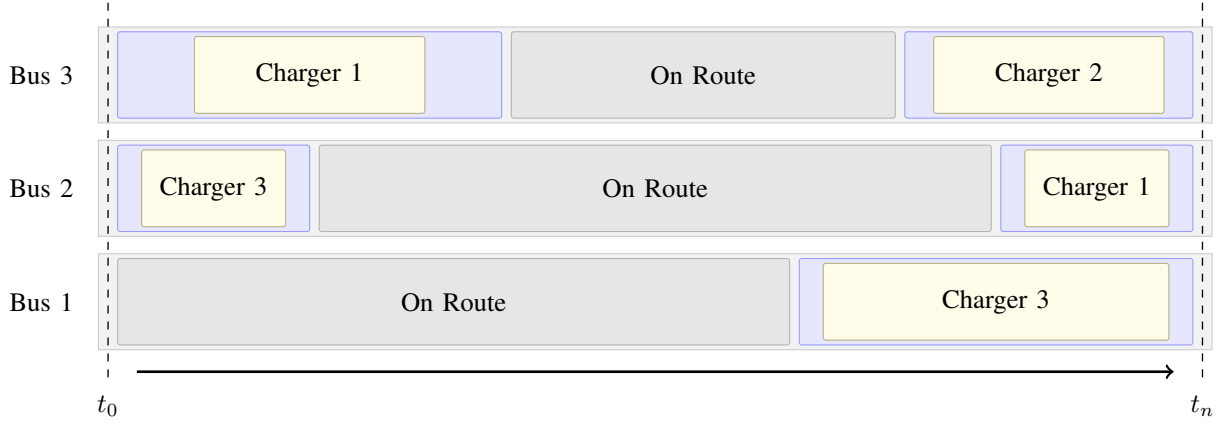


Fig. 3: Reserving time slots on chargers

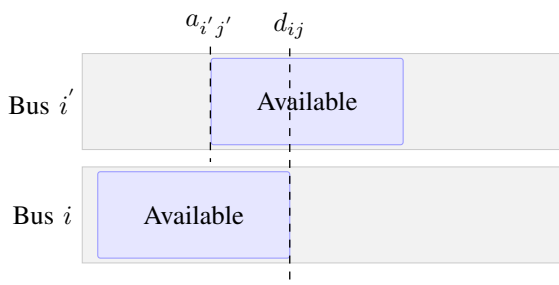


Fig. 4: Potential Overlap

simplifies to (12). Equation (13) can be expressed in standard form as

$$\begin{aligned} -c_{i'j'} + s_{ij} + M\sigma_{i'j'k} + M\sigma_{ijk} - Ml_{(ij),(i'j')} &\leq 2M \quad \forall k \\ -c_{ij} + s_{i'j'} + M\sigma_{i'j'k} + M\sigma_{ijk} + Ml_{(ij),(i'j')} &\leq 3M \quad \forall k \end{aligned} \quad (14)$$

and finally as

$$\begin{bmatrix} -1 & 0 & 0 & 1 & M & M & -M \\ 0 & 1 & -1 & 0 & M & M & M \end{bmatrix} \begin{bmatrix} c_{i'j'} \\ s_{i'j'} \\ c_{ij} \\ s_{ij} \\ \sigma_{i'j'k} \\ \sigma_{ijk} \\ l_{ij i'j'} \end{bmatrix} \leq \begin{bmatrix} 2M \\ 3M \end{bmatrix} \quad \forall k \quad (15)$$

The constraints in (14) can be repeated for all  $((i, j), (i', j')) \in \mathcal{S}$  and concatenated into a single matrix expression

$$A_4 \mathbf{y} \leq \mathbf{b}_4 \quad (16)$$

### III. BATTERY STATE OF CHARGE

BEBs must also maintain their state of charge above a minimum threshold, denoted  $h_{\min}$ . Let  $h_{ij}$  be the state of charge for bus  $i$  at the beginning of stop  $j$  as shown in Fig. 5. The initial value for bus  $i$ , denoted  $h_{i0}$ , is equal to some constant such that

$$\begin{aligned} h_{i0} &= \eta_i \quad \forall i \\ [0 & 0 \dots 0 \quad 1_i \quad 0] \mathbf{y} = \eta_i \quad \forall i \\ \tilde{A}_1 \mathbf{y} &= \tilde{\mathbf{b}}_1 \end{aligned} \quad (17)$$

and is otherwise computed as the the sum of incoming and outgoing energy where incoming energy comes from charging, and outgoing energy comes from the battery discharge. The discharge from operating bus  $i$  over route  $j$  is denoted  $\delta_{ij}$ . The increase in battery state of charge follows a linear charge model such that the increase is equal to the energy rate, denoted  $p_i$ , times the time spent charging, denoted  $\Delta_{ij}$ [25]. The total change from  $h_{ij}$  to  $h_{ij+1}$  can be expressed as

$$h_{ij+1} = h_{ij} + \Delta_{ij} \cdot p_i - \delta_{ij}. \quad (18)$$

The value for  $\Delta_{ij}$  can also be expressed in terms of the difference between  $a_{ij}$  and  $d_{ij}$  such that

$$\begin{aligned} h_{ij} + p_i \cdot (s_{ij} - c_{ij}) - \delta_i &= h_{ij+1} \\ h_{ij+1} - h_{ij} - p_i s_{ij} + p_i c_{ij} &= -\delta_i \\ [1 & -1 \quad -p_i \quad p_i] \begin{bmatrix} h_{ij+1} \\ h_{ij} \\ s_{ij} \\ c_{ij} \end{bmatrix} &= -\delta_i \quad \forall i, j \end{aligned} \quad (19)$$

The constraints for each  $i, j$  outlined in (19) can be vertically concatenated to form

$$\begin{aligned} A_{ij} \mathbf{y} &= \mathbf{b}_{ij} \quad \forall i, j \\ \tilde{A}_2 \mathbf{y} &= \tilde{\mathbf{b}}_2 \end{aligned} \quad (20)$$

Now that the state of charge is defined, the next constraint ensures that the minimum battery state of charge remains both above the minimum threshold,  $h_{\min}$ , and below the battery capacity,  $h_{\max}$ . These constraints are given as

$$\begin{aligned} -h_{ij} &\leq -h_{\min} \\ h_{ij} &\leq h_{\max} \end{aligned} \quad \forall i, j \quad (21)$$

or

$$\begin{bmatrix} 0 & \dots & 0 & -1_h & 0 & \dots & 0 \\ 0 & \dots & 0 & 1_h & 0 & \dots & 0 \end{bmatrix} \mathbf{y} \leq \begin{bmatrix} h_{\min} \\ h_{\max} \end{bmatrix} \quad \forall i, j \quad (22)$$

$$A_5 \mathbf{y} \leq \mathbf{b}_5$$

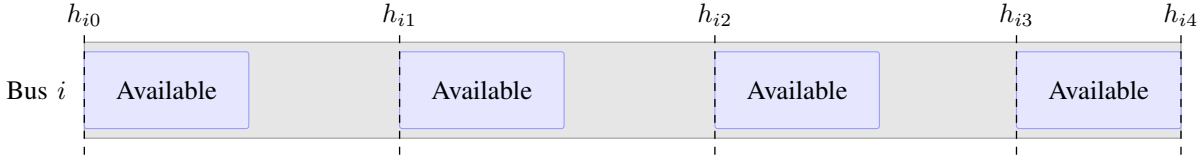
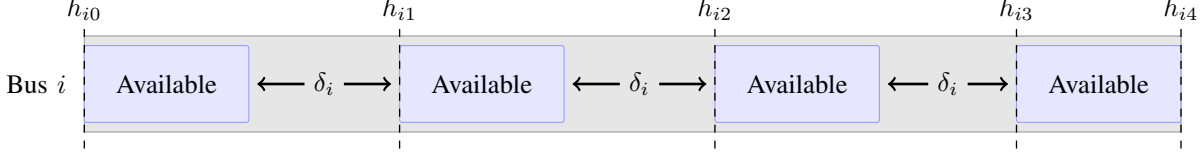


Fig. 5: State of Charge Variables

Fig. 6: Placement for  $\delta_i$ 

The final constraint has to do with the assumption that we desire to use the model for one day to predict the expected cost over a month. To do this, the state of charge at the end of the day must equal the state of charge at the beginning. Let  $h_{i,\text{end}}$  be the final daily state of charge for bus  $i$ . This is constrained to be the same as the beginning state of charge as

$$\begin{aligned} h_{i0} &= h_{i,\text{end}} \quad \forall i \\ h_{i0} - h_{i,\text{end}} &= 0 \quad \forall i. \end{aligned} \quad (23)$$

However, because equality for two continuous variables is computationally demanding, the constraint in (23) can also be expressed as

$$h_{i0} - h_{i,\text{end}} \leq 0. \quad (24)$$

Because the final state of charge is dependent on the amount of power used to charge, and power/energy use is penalized (see section V), the optimization process will drive the final state of charge down until it is nearly equal to the initial.

#### IV. INTEGRATING UNCONTROLLED LOADS

A monthly power bill is made up of several costs, two of which depend on the maximum energy consumed over 15 minutes. This 15-minute average power includes energy that is consumed by loads other than bus chargers, or “uncontrolled loads”. In practice, data for uncontrolled loads is sampled and therefore discrete. The representations for how buses use power in Section III are continuous, making their effects difficult to integrate with a discrete uncontrolled load. This section integrates these uncontrolled loads into the planning framework by converting the continuous start and end points,  $c_{ij}$  and  $s_{ij}$  from Section II, to a vector  $\mathbf{p}_{ij}$ , where the  $n^{\text{th}}$  element of the  $\mathbf{p}_{ij}$  vector represents the average power over the interval  $t_{i-1}$  to  $t_i$  from bus  $i$  during route  $j$ . The route power vectors,  $\mathbf{p}_{ij}$ , can be added together to form a discrete profile for the buses.

Let the day be divided into time segments, each of duration  $\Delta T$ . The first step is to determine the index of each segment that a bus begins charging, denoted  $k_{ij}^{\text{start}}$ , and the index of the

segment that a bus finishes charging, denoted  $k_{ij}^{\text{end}}$ . Each index can be computed as an integer multiple of  $\Delta T$  that satisfies

$$\begin{aligned} (k_{ij}^{\text{start}} - 1) \cdot \Delta T + r_{ij}^{\text{start}} &= c_{ij} \\ (k_{ij}^{\text{end}} - 1) \cdot \Delta T + r_{ij}^{\text{end}} &= s_{ij} \\ k_{ij}^{\text{start}}, k_{ij}^{\text{end}} &\in \mathbb{Z} \\ 0 < r_{ij}^{\text{start}}, r_{ij}^{\text{end}} &< \Delta T. \end{aligned} \quad (25)$$

Equation (25) yields the discrete indices  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$  along with corresponding remainder values  $r_{ij}^{\text{start}}$  and  $r_{ij}^{\text{end}}$  which will be used later in this section to calculate the average power for time segments in which buses only charge part of the time. Equation ((25)) can be rewritten in standard form and zero padded such that

$$\begin{bmatrix} \Delta T & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta T & 1 & -1 \end{bmatrix} \begin{bmatrix} k_{ij}^{\text{start}} \\ r_{ij}^{\text{start}} \\ c_{ij} \\ k_{ij}^{\text{end}} \\ r_{ij}^{\text{end}} \\ s_{ij} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \forall i, j \quad (26)$$

$$\tilde{A}_2 \mathbf{y} = \tilde{\mathbf{b}}_2.$$

and

$$\begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} k_{ij}^{\text{start}} \\ r_{ij}^{\text{start}} \\ c_{ij} \\ k_{ij}^{\text{end}} \\ r_{ij}^{\text{end}} \\ s_{ij} \end{bmatrix} \leq \begin{bmatrix} 0 \\ \Delta T \\ 0 \\ \Delta T \end{bmatrix} \quad \forall i, j \quad (27)$$

$$A_6 \mathbf{y} \leq \mathbf{b}_6.$$

The next step is to use  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$  to compute three sets of binary vectors, denoted  $\mathbf{g}_{ij}^{\text{start}}$ ,  $\mathbf{g}_{ij}^{\text{on}}$ , and  $\mathbf{g}_{ij}^{\text{end}}$ , which act as selectors for indices which correspond to charge times. The values in  $\mathbf{g}_{ij}^{\text{start}}$  and  $\mathbf{g}_{ij}^{\text{end}}$  are equal to 1 during intervals that contain energy from the remainders  $r_{ij}^{\text{start}}$  and  $r_{ij}^{\text{end}}$ . For

example, the values for  $\mathbf{g}_{ij}^{\text{start}}$  and  $\mathbf{g}_{ij}^{\text{end}}$  from the scenario in Fig. 7b would be

$$\mathbf{g}_{ij}^{\text{start}} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } \mathbf{g}_{ij}^{\text{end}} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}. \quad (28)$$

The values in  $\mathbf{g}_{ij}^{\text{on}}$  will be equal to 1 for all time indices where buses charges the entire time. For example, the values in  $\mathbf{g}_{ij}^{\text{on}}$  that correspond to Fig. 7b would be

$$\mathbf{g}_{ij}^{\text{on}} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}. \quad (29)$$

Let  $\mathbf{f}$  be a vector of one-based integer indices such that  $f_w = w \forall w \in (1, \text{nPoint})$ , where  $\text{nPoint}$  is the desired number of discrete samples. For example, if the day was discretized into 4 periods, then  $\mathbf{f}$  would be

$$\mathbf{f} = [1 \ 2 \ 3 \ 4]^T. \quad (30)$$

Defining the index as an element of  $\mathbf{f}$  allows us to convert from the single indices  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$  to the binary vectors  $\mathbf{g}_{ij}^{\text{start}}$  and  $\mathbf{g}_{ij}^{\text{end}}$  by letting

$$\begin{aligned} k_{ij}^{\text{start}} &= \mathbf{f}^T \mathbf{g}_{ij}^{\text{start}} \\ k_{ij}^{\text{end}} &= \mathbf{f}^T \mathbf{g}_{ij}^{\text{end}} \\ 1 &= \mathbf{1}^T \mathbf{g}_{ij}^{\text{start}} \\ 1 &= \mathbf{1}^T \mathbf{g}_{ij}^{\text{end}} \\ \mathbf{g}_{ij}^{\text{start}} &\in \{0, 1\}^{\text{nPoint}} \\ \mathbf{g}_{ij}^{\text{end}} &\in \{0, 1\}^{\text{nPoint}}, \end{aligned} \quad (31)$$

which can be expressed in standard form and zero padded to form a set of linear constraints.

$$\begin{bmatrix} 0 & \mathbf{0}^T & -1 & \mathbf{f}^T \\ 0 & \mathbf{1}^T & 0 & 0 \\ -1 & \mathbf{f}^T & 0 & \mathbf{0}^T \\ 0 & 0 & 0 & \mathbf{1}^T \end{bmatrix} \begin{bmatrix} k_{ij}^{\text{start}} \\ \mathbf{g}_{ij}^{\text{start}} \\ k_{ij}^{\text{end}} \\ \mathbf{g}_{ij}^{\text{end}} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} \quad \forall i, j \quad (32)$$

$$\tilde{A}_3 \mathbf{y} = \tilde{\mathbf{b}}_3.$$

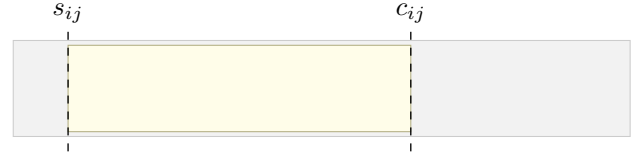
The values of  $\mathbf{g}_{ij}^{\text{on}}$  can be computed by first noticing that indices that correspond to complete charge intervals must remain between  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$ , implying that

$$\begin{cases} g_w f_w \leq k_{ij}^{\text{end}} - 1 \\ g_w f_w \geq k_{ij}^{\text{start}} + 1 \end{cases} \quad g_w = 1, \quad (33)$$

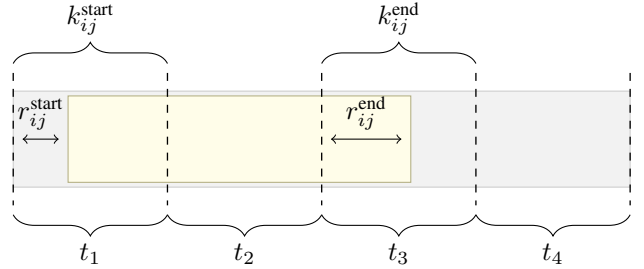
which can be expressed as a set of linear constraints such that

$$\begin{aligned} g_w \cdot f_w &\leq k_{ij}^{\text{end}} + M(1 - g_w) - 1 \\ g_w \cdot f_w &\geq k_{ij}^{\text{start}} - M(1 - g_w) + 1 \end{aligned} \quad (34)$$

where  $M$  is  $2 \cdot \text{nPoint}$ . The constraints in (34) do not require that all values between  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$  be set to one however, only that if a value is equal to one, that it must be between  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$ . For all values between  $k_{ij}^{\text{start}}$  and  $k_{ij}^{\text{end}}$  to be 1,



(a) Continuous Charging Segment



(b) Discrete Charging Segments

Fig. 7: Discretization of continuous charging intervals

the sum of  $\mathbf{g}_{ij}^{\text{on}}$  must be equal to the difference between  $k_{ij}^{\text{end}}$  and  $k_{ij}^{\text{start}}$  such that

$$\begin{aligned} g_w \cdot f_w &\leq k_{ij}^{\text{end}} + M(1 - g_w) - 1 \\ g_w \cdot f_w &\geq k_{ij}^{\text{start}} - M(1 - g_w) + 1 \\ \mathbf{1}^T \mathbf{g}_{ij}^{\text{on}} &= k_{ij}^{\text{end}} - k_{ij}^{\text{start}} - 1. \end{aligned} \quad (35)$$

The constraints in (35) work well for a general use case, however when  $k_{ij}^{\text{end}}$  is equal to  $k_{ij}^{\text{start}}$ , the last constraint in (35) becomes

$$\mathbf{1}^T \mathbf{g}_{ij}^{\text{on}} = -1. \quad (36)$$

which leads to an empty feasible set because the elements of  $\mathbf{g}_{ij}^{\text{on}}$  are all binary. Let  $k_{ij}^{\text{eq}}$  be a binary variable which is equal to 0 when  $k_{ij}^{\text{end}}$  is not equal to  $k_{ij}^{\text{start}}$ . Equation (35) can be modified to incorporate  $k_{ij}^{\text{eq}}$  to switch between the cases where  $k_{ij}^{\text{end}}$  is equal, and not equal to  $k_{ij}^{\text{start}}$  by letting

$$\begin{aligned} g_w \cdot f_w &\leq k_{ij}^{\text{end}} + M(1 - g_w) - 1 \\ g_w \cdot f_w &\geq k_{ij}^{\text{start}} - M(1 - g_w) + 1 \\ \mathbf{1}^T \mathbf{g}_{ij}^{\text{on}} &= k_{ij}^{\text{end}} - k_{ij}^{\text{start}} - k_{ij}^{\text{eq}}. \end{aligned} \quad (37)$$

and constraining  $k_{ij}^{\text{eq}}$  such that

$$\begin{aligned} k_{ij}^{\text{end}} - k_{ij}^{\text{start}} - M k_{ij}^{\text{eq}} &\leq 0 \\ -k_{ij}^{\text{end}} + k_{ij}^{\text{start}} + M k_{ij}^{\text{eq}} &\leq M. \end{aligned} \quad (38)$$

The constraints from (37) and (38) can be expressed in standard form as

$$\begin{aligned} \mathbf{1}^T \mathbf{g}_{ij}^{\text{on}} - k_{ij}^{\text{end}} + k_{ij}^{\text{start}} + k_{ij}^{\text{eq}} &= 0 \\ k_{ij}^{\text{end}} - k_{ij}^{\text{start}} - M k_{ij}^{\text{eq}} &\leq 0 \\ -k_{ij}^{\text{end}} + k_{ij}^{\text{start}} + M k_{ij}^{\text{eq}} &\leq M \\ g_w (f_w + M) - k_{ij}^{\text{end}} &\leq M - 1 \\ g_w (M - f_w) + k_{ij}^{\text{start}} &\leq M - 1. \end{aligned} \quad (39)$$

The inequality constraints from equation ((39)) imply that

$$\begin{bmatrix} f_w + M & -1 & 0 \\ M - f_w & 0 & 1 \end{bmatrix} \begin{bmatrix} g_w \\ k_{ij}^{\text{end}} \\ k_{ij}^{\text{start}} \end{bmatrix} \leq \begin{bmatrix} M - 1 \\ M - 1 \end{bmatrix} \forall g_w \in \mathbf{g}_{ij}^{\text{on}} \quad (40)$$

and that

$$\begin{bmatrix} 1 & -1 & -M \\ -1 & 1 & M \end{bmatrix} \begin{bmatrix} k_{ij}^{\text{end}} \\ k_{ij}^{\text{start}} \\ k_{ij}^{\text{eq}} \end{bmatrix} \leq \begin{bmatrix} 0 \\ M \end{bmatrix} \forall i, j, \quad (41)$$

which can be concatenated for all  $i, j$  and zero padded to form a joint matrix, satisfying

$$A_7 \mathbf{y} \leq \mathbf{b}_7. \quad (42)$$

Similarly, the equality constraint from equation ((39)) can also be concatenated and zero padded such that

$$\begin{aligned} \mathbf{1}^T \mathbf{g}_{ij}^{\text{on}} - k_{ij}^{\text{end}} + k_{ij}^{\text{start}} + k_{ij}^{\text{eq}} &= 0 \quad \forall i, j \\ \begin{bmatrix} \mathbf{1}^T & -1 & 1 & -1 \end{bmatrix} \begin{bmatrix} \mathbf{g}_{ij}^{\text{on}} \\ k_{ij}^{\text{end}} \\ k_{ij}^{\text{start}} \\ k_{ij}^{\text{eq}} \end{bmatrix} &= 0 \end{aligned} \quad (43)$$

$$\tilde{A}_4 \mathbf{y} = \tilde{\mathbf{b}}_4.$$

The next step is to define the average power during intervals that only charge for part of the time. These intervals correspond to the remainder values  $r_{ij}^{\text{start}}$  and  $r_{ij}^{\text{end}}$  and, as with previous constraints, maintain different behavior when  $k_{ij}^{\text{eq}} = 0$  and  $k_{ij}^{\text{eq}} = 1$ . The average power that corresponds to  $r_{ij}^{\text{start}}$  and  $r_{ij}^{\text{end}}$  can be computed as

$$\begin{cases} p_{ij}^{\text{start}} = \frac{p \cdot (\Delta T - r_{ij}^{\text{start}})}{\Delta T} & k_{ij}^{\text{eq}} = 1 \\ p_{ij}^{\text{end}} = \frac{p \cdot r_{ij}^{\text{end}}}{\Delta T} & \\ p_{ij}^{\text{start}} = \frac{p \cdot (r_{ij}^{\text{end}} - r_{ij}^{\text{start}})}{\Delta T} & k_{ij}^{\text{eq}} = 0 \\ p_{ij}^{\text{end}} = 0 & \end{cases}, \quad (44)$$

where  $p$  is the charge rate. Equation (44) can also be expressed as a set of linear inequality constraints such that

$$\begin{aligned} p_{ij}^{\text{start}} &\leq p - \frac{p}{\Delta T} r_{ij}^{\text{start}} + M(1 - k_{ij}^{\text{eq}}) \\ p_{ij}^{\text{start}} &\geq p - \frac{p}{\Delta T} r_{ij}^{\text{start}} - M(1 - k_{ij}^{\text{eq}}) \\ p_{ij}^{\text{start}} &\leq \frac{p}{\Delta T} r_{ij}^{\text{end}} - \frac{p}{\Delta T} r_{ij}^{\text{start}} + M k_{ij}^{\text{eq}} \\ p_{ij}^{\text{start}} &\geq \frac{p}{\Delta T} r_{ij}^{\text{end}} - \frac{p}{\Delta T} r_{ij}^{\text{start}} - M k_{ij}^{\text{eq}} \\ p_{ij}^{\text{end}} &\leq \frac{p}{\Delta T} r_{ij}^{\text{end}} + M(1 - k_{ij}^{\text{eq}}) \\ p_{ij}^{\text{end}} &\geq \frac{p}{\Delta T} r_{ij}^{\text{end}} - M(1 - k_{ij}^{\text{eq}}) \\ p_{ij}^{\text{end}} &\leq M k_{ij}^{\text{eq}} \\ p_{ij}^{\text{end}} &\geq -M k_{ij}^{\text{eq}}, \end{aligned} \quad (45)$$

where  $M$  is the battery capacity, and can be expressed in standard form as

$$\begin{aligned} p_{ij}^{\text{start}} + \frac{p}{\Delta T} r_{ij}^{\text{start}} + M k_{ij}^{\text{eq}} &\leq M + p \\ -p_{ij}^{\text{start}} - \frac{p}{\Delta T} r_{ij}^{\text{start}} + M k_{ij}^{\text{eq}} &\leq M - p \\ p_{ij}^{\text{start}} - \frac{p}{\Delta T} r_{ij}^{\text{end}} + \frac{p}{\Delta T} r_{ij}^{\text{start}} - M k_{ij}^{\text{eq}} &\leq 0 \\ -p_{ij}^{\text{start}} + \frac{p}{\Delta T} r_{ij}^{\text{end}} - \frac{p}{\Delta T} r_{ij}^{\text{start}} - M k_{ij}^{\text{eq}} &\leq 0 \\ p_{ij}^{\text{end}} - \frac{p}{\Delta T} r_{ij}^{\text{end}} + M k_{ij}^{\text{eq}} &\leq M \\ -p_{ij}^{\text{end}} + \frac{p}{\Delta T} r_{ij}^{\text{end}} + M k_{ij}^{\text{eq}} &\leq M \\ p_{ij}^{\text{end}} - M k_{ij}^{\text{eq}} &\leq 0 \\ -p_{ij}^{\text{end}} - M k_{ij}^{\text{eq}} &\leq 0 \end{aligned} \quad (46)$$

and by using matrix multiplication such that

$$\begin{bmatrix} 1 & 0 & \frac{p}{\Delta T} & 0 & M \\ -1 & 0 & -\frac{p}{\Delta T} & 0 & M \\ 1 & 0 & \frac{p}{\Delta T} & -\frac{p}{\Delta T} & -M \\ -1 & 0 & -\frac{p}{\Delta T} & \frac{p}{\Delta T} & -M \\ 0 & 1 & 0 & -\frac{p}{\Delta T} & M \\ 0 & -1 & 0 & \frac{p}{\Delta T} & M \\ 0 & 1 & 0 & 0 & -M \\ 0 & -1 & 0 & 0 & -M \end{bmatrix} \begin{bmatrix} p_{ij}^{\text{start}} \\ p_{ij}^{\text{end}} \\ r_{ij}^{\text{start}} \\ r_{ij}^{\text{end}} \\ k_{ij}^{\text{eq}} \end{bmatrix} \leq \begin{bmatrix} M + p \\ M - p \\ 0 \\ 0 \\ M \\ M \\ 0 \\ 0 \end{bmatrix} \quad \forall i, j$$

$$A_8 \leq \mathbf{b}_8 \quad (47)$$

where  $p_{ij}^{\text{start}}$ ,  $p_{ij}^{\text{end}}$ , and  $p$  represent the average power that corresponds to  $r_{ij}^{\text{start}}$ ,  $r_{ij}^{\text{end}}$ , and full charging intervals respectively. The total average power use is calculated as

$$\mathbf{P}_{\text{total}} = \bar{\mathbf{p}}_{\text{load}} + \sum_{ij} \mathbf{g}_{ij}^{\text{start}} \cdot p_{ij}^{\text{start}} + \mathbf{g}_{ij}^{\text{on}} \cdot p + \mathbf{g}_{ij}^{\text{end}} \cdot p_{ij}^{\text{end}} \quad (48)$$

where  $\bar{\mathbf{p}}_{\text{load}}$  is the average power of the uncontrolled loads.

Note, however that (48) contains the bilinear terms  $\mathbf{g}_{ij}^{\text{start}} \cdot p_{ij}^{\text{start}}$  and  $\mathbf{g}_{ij}^{\text{end}} \cdot p_{ij}^{\text{end}}$ . The expression  $\mathbf{g}_{ij}^{\text{start}} \cdot p_{ij}^{\text{start}}$  from (48) can be thought of as a vector,  $\mathbf{p}_{ij}^{\text{start}}$  which contains values for  $p_{ij}^{\text{start}}$  whenever  $g_{ij}^{\text{start}}$  is not equal to 0 such that

$$\left. \begin{aligned} p_w &= p_{ij}^{\text{start}} & g_w &= 1 \\ p_w &= 0 & g_w &= 0 \end{aligned} \right\} \forall p_w \in \mathbf{p}_{ij}^{\text{start}}, \quad (49)$$

which can be rewritten as a set of linear inequality constraints such that

$$\begin{aligned} p_w &\geq p_{ij}^{\text{start}} - M(1 - g_w) \forall p_w \in \mathbf{p}_{ij}^{\text{start}} \\ p_w &\leq p_{ij}^{\text{start}} + M(1 - g_w) \forall p_w \in \mathbf{p}_{ij}^{\text{start}} \\ p_w &\geq -M g_w \forall p_w \in \mathbf{p}_{ij}^{\text{start}} \\ p_w &\leq M g_w \forall p_w \in \mathbf{p}_{ij}^{\text{start}} \end{aligned} \quad (50)$$

The same approach can be taken to replace  $\mathbf{g}_{ij}^{\text{end}} \cdot p_{ij}^{\text{end}}$  with the vector  $\mathbf{p}_{ij}^{\text{end}}$  by letting

$$\begin{aligned} p_w &\geq p_{ij}^{\text{end}} - M(1 - g_w) \forall p_w \in \mathbf{p}_{ij}^{\text{end}} \\ p_w &\leq p_{ij}^{\text{end}} + M(1 - g_w) \forall p_w \in \mathbf{p}_{ij}^{\text{end}} \\ p_w &\geq -M g_w \forall p_w \in \mathbf{p}_{ij}^{\text{end}} \\ p_w &\leq M g_w \forall p_w \in \mathbf{p}_{ij}^{\text{end}}, \end{aligned} \quad (51)$$

	On-Peak	Off-Peak	Both
Energy	On-Peak Energy Charge	Off-Peak Energy Charge	None
Energy Rate	$u_{e-on}$	$u_{e-off}$	None
Power	Demand Charge	None	Facilities Charge
Power Rate	$u_{p-on}$	None	$u_{p-all}$

Fig. 8: Description of the assumed billing structure

which can be written in standard form, stacked to accomodate the constraints for all  $i, j$ , and zero padded in the usual fashion as

$$\begin{bmatrix} -1 & 1 & M \\ 1 & -1 & M \\ -1 & 0 & -M \\ 1 & 0 & -M \end{bmatrix} \begin{bmatrix} p_w \\ p_{ij}^{start} \\ g_w \end{bmatrix} \leq \begin{bmatrix} M \\ M \\ 0 \\ 0 \end{bmatrix} \quad \forall p_w \in \mathbf{p}_{ij}^{start} \quad (52)$$

$$A_9 \leq \mathbf{b}_9.$$

Equation (51) can be expressed in standard form, stacked for all  $i, j$ , and zero padded in a similar fashion such that

$$\begin{bmatrix} -1 & 1 & M \\ 1 & -1 & M \\ -1 & 0 & -M \\ 1 & 0 & -M \end{bmatrix} \begin{bmatrix} p_w \\ p_{ij}^{end} \\ g_w \end{bmatrix} \leq \begin{bmatrix} M \\ M \\ 0 \\ 0 \end{bmatrix} \quad \forall p_w \in \mathbf{p}_{ij}^{end} \quad (53)$$

$$A_{10} \mathbf{y} \leq \mathbf{b}_{10}.$$

An expression for the total power used can then be expressed as

$$\mathbf{p}^{total} = \mathbf{p}^{load} + \sum_{ij} \mathbf{p}_{ij}^{start} + \mathbf{p}_{ij}^{end} + \mathbf{g}_{ij}^{on} \cdot p \quad (54)$$

and in standard form as

$$\begin{bmatrix} 1 & -1^{start} & -1^{end} & -1^{on} \cdot p \end{bmatrix} \begin{bmatrix} \mathbf{p}_w^{total} \\ \mathbf{p}_w^{start} \\ \mathbf{p}_w^{end} \\ \mathbf{g}_w^{on} \end{bmatrix} = \mathbf{p}_w^{load} \quad (55)$$

$$\tilde{A}_4 \mathbf{y} = \tilde{\mathbf{b}}_4$$

## V. OBJECTIVE FUNCTION

This work adopts the objective function developed in [19], which implements the rate schedule from [22]. The rate schedule in [22] is based off of two primary components: power and energy.

Power is billed per kW for the highest 15 minute average power over a fixed period of time. It is common practice for power providers to use a higher rate during “on-peak” periods when power is in higher demand and use a lower rate during “off-peak” hours, which account for all other time periods.

The rate schedule given in [22] assesses a fee for a users maximum average power during on-peak hours called the On-Peak Power charge, and a user’s overall maximum average power, called a facilities charge as shown in figure 8.

Energy fees are also assessed per kWh of energy consumed with a higher rate for energy consumed during on-peak hours and a lower rate for energy consumed during off-peak hours.

### A. Power Charges

It is necessary to compute the maximum power both overall and for on-peak periods. Section IV adopted the convention that  $\Delta T$  denotes the time offset between power samples and that each power reading would reflect the average power used in the previous interval. Now let us set  $\Delta T$  to 15 minutes, making  $\mathbf{p}^{total}$  an expression of the 15 minute average power. Next, let  $\mathcal{S}_{on}$  be the set of all indices belonging to on-peak time periods such that  $j \in \mathcal{S}_{on}$  implies that the  $j^{th}$  element of  $\mathbf{p}^{total}$ ,  $p_j^{total}$ , represents a 15 minute average during an on-peak interval and let  $q_{on}$  be the maximum on-peak average power. With these definitions, constraints for determining the maximum on-peak average are defined as

$$\begin{aligned} p_j^{total} &\leq q_{on} \quad \forall j \in \mathcal{S}_{on} \\ [1 \quad -1] \begin{bmatrix} p_j^{total} \\ q_{on} \end{bmatrix} &\leq 0 \quad \forall j \in \mathcal{S}_{on} \\ A_{11} \mathbf{y} &\leq \mathbf{0} \\ A_{11} \mathbf{y} &\leq \mathbf{b}_{11} \end{aligned} \quad (56)$$

Because an increased value in  $q_{on}$  is directly related to an increase in cost, the optimizer will minimize  $q_{on}$  until it is equal to the maximum value in  $\{p_j^{total} \mid \forall j \in \mathcal{S}_{on}\}$ . A similar procedure can be used to derive a set of constraints for the overall maximum average power, denoted  $q_{all}$ , and is represented as

$$\begin{aligned} A_{12} \mathbf{y} &\leq \mathbf{0} \\ A_{12} \mathbf{y} &\leq \mathbf{b}_{12}. \end{aligned} \quad (57)$$

The charges for power are then expressed as

$$\begin{aligned} \text{power cost} &= q_{on} \cdot u_{p-on} + q_{all} \cdot u_{p-all} \\ &= [u_{p-on} \quad u_{p-all}] \begin{bmatrix} q_{on} \\ q_{all} \end{bmatrix} \\ &= \mathbf{u}_p^T \mathbf{y} \end{aligned} \quad (58)$$

where  $u_{p-on}$  is the rate per kW for on-peak power use, or the demand charge and  $u_{p-all}$  is the rate per kW for the overall maximum 15 minute average.

### B. Energy Charges

Energy is defined as the integral of power over a length of time. Because the values for power given in this work reflect an average power, the energy over a given period can be computed by multiplying the average power by the change in time, or  $\Delta T$  such that

$$\text{Total Energy} = \mathbf{1}^T \mathbf{p}^{total} \cdot \Delta T. \quad (59)$$

However, because the energy is billed for on-peak and off-peak time periods, we define two binary vectors  $\mathbf{1}_{on}$  and  $\mathbf{1}_{off}$



such that  $1_j^{\text{on}} = 1 \ \forall j \in S_{\text{on}}$  and zero otherwise. Similarly,  $1_{\text{off}} = \mathbf{1} - 1_{\text{on}}$ . The on-peak and off-peak energy can then be computed as

$$\begin{aligned} \text{On-Peak Energy} &= \mathbf{1}_{\text{on}}^T \mathbf{p}_{\text{total}} \cdot \Delta T \\ \text{Off-Peak Energy} &= \mathbf{1}_{\text{off}}^T \mathbf{p}_{\text{total}} \cdot \Delta T. \end{aligned} \quad (60)$$

Let  $u_{\text{e-on}}$  and  $u_{\text{e-off}}$  represent the on-peak and off-peak energy rates respectively. The total cost for energy is computed as

$$\begin{aligned} \text{Energy Cost} &= (\mathbf{1}_{\text{on}} \cdot u_{\text{e-on}} \cdot \Delta T)^T \mathbf{p}_{\text{total}} + (\mathbf{1}_{\text{off}} \cdot u_{\text{e-off}} \cdot \Delta T)^T \mathbf{p}_{\text{total}} \\ &= (\mathbf{u}_{\text{e-on}} + \mathbf{u}_{\text{e-off}})^T \mathbf{p}_{\text{total}} \\ &= \mathbf{u}_{\text{e}}^T \mathbf{y} \end{aligned} \quad (61)$$

### C. Cost Function and Final Problem

The entire cost function is given as the sum of the energy and power costs such that

$$\begin{aligned} \text{Cost} &= \mathbf{u}_{\text{p}}^T \mathbf{y} + \mathbf{u}_{\text{e}}^T \mathbf{y} \\ &= (\mathbf{u}_{\text{p}} + \mathbf{u}_{\text{e}})^T \mathbf{y} \\ &= \mathbf{v}^T \mathbf{y} \end{aligned} \quad (62)$$

The complete problem can now be formulated as

$$\begin{aligned} \min_{\mathbf{y}} \quad & \mathbf{y}^T \mathbf{v} \text{ subject to} \\ & \tilde{\mathbf{A}}_{1:3} \mathbf{y} = \tilde{\mathbf{b}}_{1:3} \quad \mathbf{A}_{1:12} \mathbf{y} \leq \mathbf{b}_{1:12} \end{aligned} \quad (63)$$

or

$$\begin{aligned} \min_{\mathbf{y}} \quad & \mathbf{y}^T \mathbf{g} \text{ subject to} \\ & \tilde{\mathbf{A}} \mathbf{y} = \tilde{\mathbf{b}}, \quad \mathbf{A} \mathbf{y} \leq \mathbf{b}. \end{aligned} \quad (64)$$

## VI. RESULTS

This section shows performance for the proposed bus charging algorithm and contains three subsections. Section VI-A compares the proposed method with a previously published algorithm [11]. Section VI-B discusses the difference in computation time between prior work and the current method.

The comparisons in this section consider a 5 bus 5 charger scenario with a charge rate of 300 kW. Each solution is expressed in terms of a MILP and solved up to a 2% gap using Gurobi [10] unless otherwise specified. The uncontrolled loads from section IV are represented with a scaled version of historical data from the Trax Power Substation at UTA. The scaling served to increase the difficulty of the charging problem and better illustrates the capabilities of the proposed algorithm.

### A. Cost Comparison with Prior Work

This section compares the monthly cost of energy for the proposed method with two other methods. The first method is a baseline algorithm that simulates how bus drivers at the Utah Transit Authority (UTA) in Salt Lake City (SLC) charge by default. The second method comes from [11], which was selected because it is very similar to the proposed algorithm. The charge plan for all three methods is computed using mixed integer linear programs as described below.

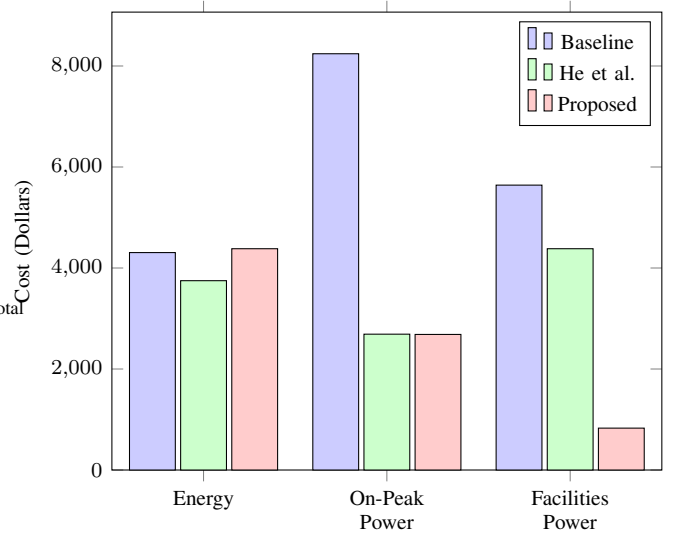


Fig. 9: Cost comparison with prior work

Conversations with bus drivers at the UTA in SLC have shown that bus drivers generally top off their batteries whenever a charger is available. In essence, the bus drivers are solving a maximization problem by default as they maximise the number of charge sessions in a day. Hence, the baseline algorithm follows the constraints in Eqn. (63) but incentivizes buses to charge as frequently as possible. Let  $v_{\sigma}^{ijk}$  be the value of the objective function  $v$  at the index corresponding to  $\sigma_{ijk}$  from section II-B. By letting  $v_{\sigma}^{ijk} = -1, \forall i, j, k$  and zero otherwise, the baseline method effectively maximizes the number of times a bus can charge. All methods are evaluated according to the rate schedule in [22].

A comparison of all three algorithms is given in Fig. 9. Note how the cost of energy is generally the same for each algorithm and that the primary differences in cost come from the on-peak and facilities power charges, illustrating the need to minimize peak average power. To understand the difference in power management between the baseline and the proposed method, refer to Fig. 10. Note how the power for the proposed method (blue line) is almost completely flat, indicating a steady power use. In comparison, the baseline algorithm (red line) is less steady and includes periods of high power use, which leads to the increased power charges in Fig. 9.

A similar phenomena is observed when comparing the proposed method to [11]. Fig. 11 compares the timing of charge requirements for the proposed algorithm and [11]. Note how the proposed algorithm yields a charge profile that is complementary to the uncontrolled load. When the uncontrolled load increases the bus load decreases and yields a flat load profile, whereas the load profile from [11] only minimizes charging during on-peak loads. The ability to produce a consistent load profile improves upon [11] because it accounts for the effects of uncontrolled loads and costs of average power.

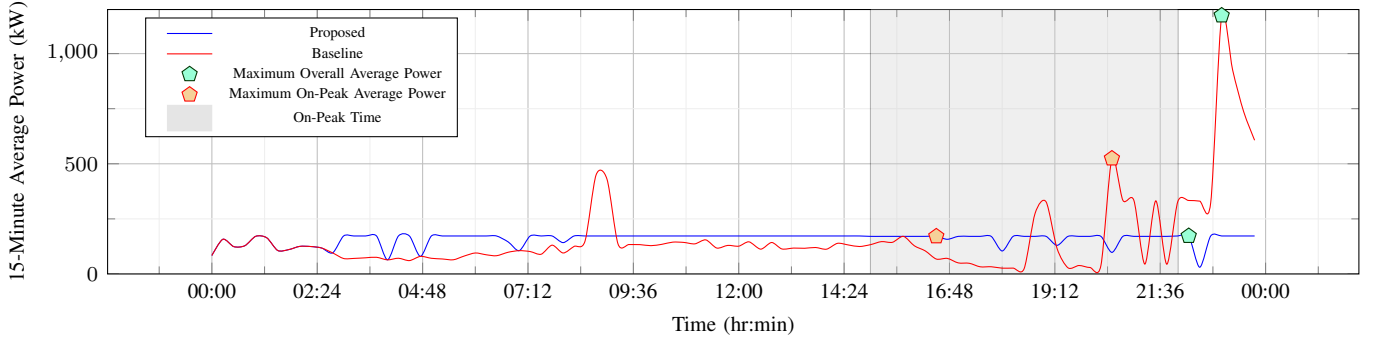


Fig. 10: 15-Minute average power for one day

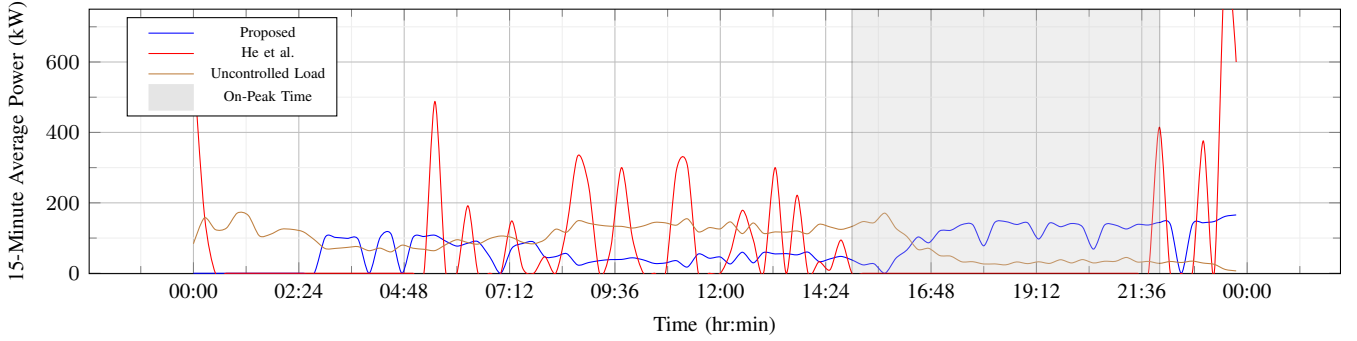


Fig. 11: Comparison between uncontrolled and bus loads

### B. Computation Time

As explained in the introduction, one motivation for this work was to extend the work by [19] to include the benefits while avoiding the pitfalls of computation complexity. This section shows a comparison of work by [19] which uses a network flow approach and discrete time axis to solve the charge problem. Because both the approach in [19] and the approach in this paper include the full rate schedule, their monthly costs are comparable. However, because the approach from [19] handles the time component discretely, higher fidelity time estimates become computationally prohibitive.

Fig. 12 compares the computation time for the proposed algorithm with [19] with a time step of one minute. The algorithms were run on a common desktop computer with 32 Gb of RAM and an 8 core 4 Gz processor and the method from [19] was solved up to a 5% gap. Note how the computation time for the proposed algorithm is several orders of magnitude less and gives the added benefit of floating point precision in its time estimates.

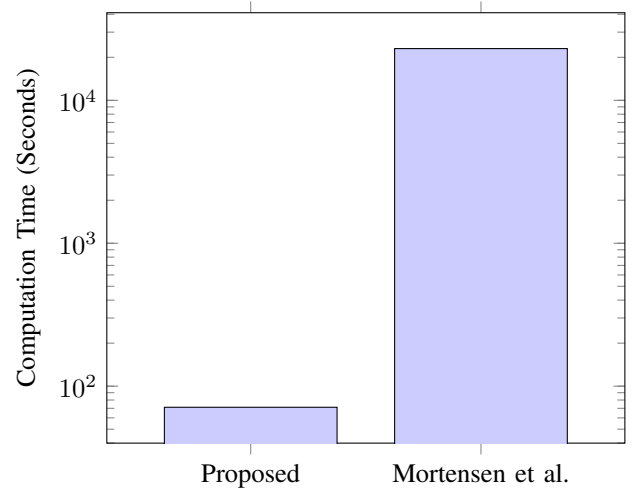


Fig. 12: Comparison of computation time between the proposed algorithm and [19]

## VII. CONCLUSIONS AND FUTURE WORK

In conclusion, the proposed method yields significant cost savings over the work given in [11] and the default charging behavior at the UTA site. This is accomplished by minimising on-peak energy, on-peak power, and overall average power in the presence of uncontrolled loads. Additionally, by parameterising the charge sessions with continuous time variables, we have reduced the computational work by several orders of magnitude compared to prior work [19], which used a

discrete time approach. The reduction in complexity suggests that this method could be explored for the problem of real-time planning.

Future work might integrate approximate solutions from simpler heuristic approaches to initialize the MILP solver to accelerate convergence. Another known limitation includes how the computational complexity for the current method does not scale with large numbers of buses (more than 30). For larger bus fleets, a decentralized as opposed to a global method might work better.

Finally, this method does not account for uncertainty in the model. Stochastic events such as arrival times, deviations in uncontrolled loads, and battery discharge can significantly affect the useability of the global plan. Accounting for stochastic models of variability can add robustness to the charging solution.

## REFERENCES

- [1] Poornesh et al. "A Comparative study on Electric Vehicle and Internal Combustion Engine Vehicles". In: *2020 Internat. Conf. on Smart Electronics and Communication*.
- [2] Yaseen Alwesabi, Farzad Avishan, Ihsan Yanikoglu, Zhaocai Yiu, and Yong Wang. "Robust strategic planning of dynamic wireless charging infrastructure for electric buses". In: *Applied Energy* (2022).
- [3] Avishan Bagherinezhad, Alejandro D. Palomino, Bosong Li, and Masood Parvania. "Spatio-Temporal Electric Bus Charging Optimization With Transit Network Constraints". In: *IEEE Transactions on Industry Applications* (2020).
- [4] Bhagyashree J Balde and Arghya Sardar. "Electric Road system With Dynamic Wireless charging of Electric buses". In: *IEEE Trans. Electrification Conf.* 2019.
- [5] T. Boonraksa, A. Paudel, P. Dawan, and B. Marungsri. "Impact of Electric Bus Charging on the Power Distribution System a Case Study IEEE 33 Bus Test System". In: *IEEE Grand Internat. Conf. and Exposition Asia*. 2019.
- [6] Alexander Brown, Greg Droge, Mario Harper, and Jacob Gunther. "A Position Allocation Approach to the Scheduling of Battery Electric Bus Charging". In: (2020).
- [7] Qifu Cheng, Lei Chen, Qiuye Sun, Rui Wang, and Dazhong Ma. "A smart charging algorithm-based fast charging station with energy storage system-free". In: (2020).
- [8] Bálint Csonka. "Optimization of Static and Dynamic Charging Infrastructure for Electric Buses". In: *Energies* (2021).
- [9] Sanchari Deb, Karuna Kalita, and Pinakeshwar Mahanta. "Impact of electric vehicle charging stations on reliability of distribution network". In: *IEEE Internat. Conf. on Tech. Adv. in Power and Energy*. 2017.
- [10] Gurobi Optimization, LLC. *Gurobi Optimizer Reference Manual*. 2022. URL: <https://www.gurobi.com>.
- [11] Yi He, Ziqi Song, and Zhaocai Liu. "Fast-charging station deployment for battery electric bus systems considering electricity demand charges". In: *Sustainable Cities and Society* (2019).
- [12] Adnane Houbbadi, Eduardo Redondo-Iglesias, Rochdi Trigui, Serge Pelissier, and Tanguy Bouton. "Optimal Charging Strategy to Minimize Electricity Cost and Prolong Battery Life of Electric Bus Fleet". In: *IEEE Vehicle Power and Propulsion Conf.* 2019.
- [13] Shubham Jain, Zaurez Ahmad, Mohammad Saad Alam, and Yasser Rafat. "Battery Swapping Technology". In: *IEEE Internat. Conf. on Recent Advances and Innovations in Engineering*. 2020.
- [14] Seog Y. Jeong, Jun H. Park, Gwang P. Hong, and Chun T. Rim. "Automatic Current Control by Self-Inductance Variation for Dynamic Wireless EV Charging". In: *IEEE Workshop on Emerg. Tech.: Wireless Power Transfer*. June 2018.
- [15] Hideki Kato, Ryosuke Ando, Yoshinori Kondo, Tsutomu Suzuki, Keisuke Matsushashi, and Shinji Kobayashi. "Comparative measurements of the eco-driving effect between electric and internal combustion engine vehicles". In: *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*. 2013.
- [16] Rong-Ceng Leou and Jeng-Jiun Hung. "Optimal Charging Schedule Planning and Economic Analysis for Electric Bus Charging Stations". In: *Energies* (2017).
- [17] Ning Ma and Zhili Zhou. "Mixed-integer Programming Model for Two-dimensional Non-guillotine Bin Packing Problem with Free Rotation". In: *Internat. Conf. for Information Science and Control Engineering*. 2017.
- [18] Moataz Mahmoud, Ryan Garnett, Mark Ferguson, and Pavlos Kanaroglou. "Electric buses: A review of alternative powertrains". In: *Renewable and Sustainable Energy Reviews* (2016).
- [19] Daniel Mortensen, Jacob Gunther, Greg Droge, and Justin Whitaker. "Comprehensive Cost Minimization for Charging Electric Bus Fleets". In: *IEEE Transactions on Intelligent Transportation Systems, In Review* (2021).
- [20] Nanduni I. Nimalsiri, Chathurika P. Mediwaththe, Elizabeth L. Ratnam, Marnie Shaw, David B. Smith, and Saman K. Halgamuge. "A Survey of Algorithms for Distributed Charging Control of Electric Vehicles in Smart Grid". In: *IEEE Transactions on Intelligent Transportation Systems* (2020).
- [21] Inaki Ojer, Alberto Berrueta, Julio Pascual, Pablo Sanchis, and Alfredo Ursua. "Development of energy management strategies for the sizing of a fast charging station for electric buses". In: *IEEE International Conference on Environment and Electrical Engineering*. 2020.
- [22] Rocky Mountain Power. *Rocky Mountain Power Electric Service Schedule No. 8*. 2021. URL: [https://www.rockymountainpower.net/content/dam/pcorp/documents/en/rockymountainpower/rates-regulation/utah/rates/008\\_Large\\_General\\_Service\\_1\\_000\\_kW\\_and\\_Over\\_Distribution\\_Voltage.pdf](https://www.rockymountainpower.net/content/dam/pcorp/documents/en/rockymountainpower/rates-regulation/utah/rates/008_Large_General_Service_1_000_kW_and_Over_Distribution_Voltage.pdf).
- [23] Nan Qin, Azwirman Gusrialdi, R. Paul Brooker, and Ali T-Raissi. "Numerical analysis of electric bus fast charging strategies for demand charge reduction". In: *Trans. Research Part A: Policy and Practice* (2016).
- [24] Marco Rinalde, Erika Picarelli, Andrea D'Ariano, and Francesco Viti. "Mixed-fleet single-terminal bus scheduling problem: Modeling, solution scheme and potential applications". In: *Omega* (2020).

- [25] Xiaoxue Rong, Bo Wang, Chuanjun Shao, Guangyuan Yu, Yan'an Wang, Qiming Sun, and Zhaohong Bie. "Coordinated charging strategy of electric vehicle charging station based on combination of linear power flow and genetic algorithm". In: *IEEE Asia-Pacific Power and Energy Engineering Conf.* 2016.
- [26] Daniel Stahleder, David Reihs, Stephan Ledinger, and Felix Lehfuss. "Impact Assessment of High Power Electric Bus Charging on Urban Distribution Grids". In: *IEEE Industrial Electronics Society*. 2019.
- [27] Guang Wang, Xiaoyang Xie, Fan Zhang, Yunhuai Liu, and Desheng Zhang. "BCharge: Data-Driven Real-Time Charging Scheduling for Large-Scale Electric Bus Fleets". In: *Proceedings - Real-Time Systems Symposium* (2019).
- [28] Ran Wei, Xiaoyue Liu, Yi Ou, and S. Kiavash Fayyaz. "Optimizing the spatio-temporal deployment of battery electric bus system". In: *Journal of Transport Geography* (2018).
- [29] Justin Whitaker, Greg Droge, Matthew Hansen, Daniel Mortensen, and Jacob Gunther. "A Network Flow Approach to Battery Electric Bus Scheduling, in review". In: *IEEE Transactions on Intelligent Transportation Systems* (2022).
- [30] Xian Zhang and Guibin Wang. "Optimal dispatch of electric vehicle batteries between battery swapping stations and charging stations". In: *IEEE Power and Energy Society General Meeting*. 2016.
- [31] Yirong Zhou, Liu Xiaoyue, Wei Ran, and dummy. "Bi-Objective Optimization for Battery Electric Bus Deployment Considering Cost and Environmental Equity". In: *IEEE Trans. on Intel. Transportation Systems* (2021).