Daniel's Super Cool and overly long title

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***Abstract*—TODO: add abstract**

***Index Terms*—TODO: Add Keywords**

I. Introduction

Recent calls for a reduced carbon footprint have pushed transit authorities to adopt electric buses (EB). Conversion to EB reduces environmental impact as EB provide zero emissions and access to renewable energy [14].

These benefits are possible because EB draw power from electrical infrastructure. The loads introduced by charging are substantial and can exceed the grid capacity [16][6][3], requiring prohibitively expensive upgrades. The cost of upgrading is reflected in the billing structure used by power providers and can make large-scale charging undesireable for consumers.

One approach to reducing charge costs, is to defer premature upagrades by efficiently managing how buses charge. However, developing charge plans must consider a number of factors. For example, all buses must maintain a minimum charge level while adhering to route schedules. Batteries must also have sufficient charge time and share a limited number of chargers. The focus of this work is to find an optimal charge schedule which meets these requirements while minimising expenses from grid use. This problem is refered to hereafter as the 'bus charge problem'.

Because the number of fast-chargers is limited, a bus may only charge if a charger is available and must leave on route as scheduled. Furthermore, because batteries may require several hours for a full charge, they may not have time finish. Lower charge rates may also be used for less power draw which further delays charge times.

At the end of operation hours, each bus is stored in the bus depot and connected to a 'slow' charger. Slow-charging is preferable when possible because it draws less instantaneous power and prolongs battery life [9]. Furthermore, charging during off-hours offers each bus the opportunity to charge at any time with no contention for charging resources. The buses reside in the bus depot until the next morning when they depart for their first stop.

To maintain the bus battery state of charge in a nominal operations environment, there are several factors to consider including route schedules, on/off peak hours, additional grid loads, and the charge needs of individual buses. Finding a fiscally optimal charge schedule is refered to hereafter as the 'bus charge problem' and is the focus of this paper.

The remainder of this paper is organized as follows: Section II gives a description of previous work for solving the charge problem and Section III describes the directed graph framework used for describing the operations environment. Section IV extends the content of III to multi-graph solutions, and Section V describes a set of linear constraints that describe the battery charge dynamics. Sections VI and VII describe the rate schedule used for billing and how this is phrased as an objective function to minimize. Finally, Sections VIII, IX, and X briefly describe the optimization software used to solve the mixed integer linear program as developed in previous sections, present results, and describe future work.

II. Literature Review

We acknowledge the existance of additional contributions, such as minimizing costs for startup infrastructure [17], and preserving battery lifespan [9]. However, as these are not relevent to this work, we consider them outside the scope of this review. We further acknowledge that some works cited herein contain solutions to several of these problems, such as in [20], but for sake of organization, we list them in the most relevent context.

A. Battery Charging

Here we consider solutions to empty batteries and focus our attention on either battery replacement or charging methods. We also refer to charging methods as either static (at rest) or dynamic (in motion).

Because charge times can significantly complicate logistics, [19] and [11] give methods for exchanging spent with charged batteries. The benefits include minimal down time as refueling can occur in a matter of minutes. Unfortunately, batteries can be cumbersome, and their exchange can be difficult. It also requires specialized tools, and could require automation.

Another alternative is to inductively charge buses while they traverse their routes [2], [11], [12], [5]. Unfortunately, this requires significant infrastructure which may not be available and is cost prohibitive for large systems.

Alternative solutions tend towards optimal planning. This allows for buses to charge in the traditional sense, minimizes additional infrastructure, and avoids the complexities of exchanging batteries. These approaches generally fall into one of three categories; reactive, hybrid, and global.

Reactive planning focuses strictly on presential circumstances. Methods of this type are computationally efficient, run in real-time, and are adaptable. These techniques generally stem from control theory and minipulate a current state to minimize cost. One such example includes the work done by [4], who uses comparable methodology to reduce demand on the power grid. This methodology however, does not account for global phenomena that require broader planning schemes and for the most part this class of technqiues remain unused for bus charging.

Another class of algorithms encompasses a limited number of projected events to improve decision making. This allows for a middle ground between simplicity and global planning and has proven useful in previous work [10], [1].

Global planning algorithms assume comlplete foreknowledge of future events and provide globally optimal plans [18],[7]. This class of algorithm requires more computation and is less flexible then reactive or hybrid approaches. However, the solutios are globally optimal and derive from insight unavailable to other algorithm classes.

B. *Cost Management*

The final set of constraints aim to decrease load on the grid. Previous work has shown that the use of electric buses can significantly complicate local power management [3] [6]. Additinally, power demand generally increases the fiscal cost from a billing perspective. [8] has provided methodology for forcasing the load on the grid. These types of models often form the basis for power distribution algorithms. For example, [15] gives an approach to minimize grid demand, but requires foreknowledge of uncontrolled loads. [4] takes a different approach and observes real-time data to control the charge rates of connected buses. [13] also operates in the real-time sense but uses on-board batteries to mitigate the effects of rapid charging.

III. Graph Based Problem Formulation

A solution to the bus charge problem must reveal *what* to charge and *when* to charge it. These two questions suggest a two dimensional solution where the first dimension describes *when* and the second answers *what*. The first dimension represents time as a set of discrete indices $t_0, t_1, \ldots, t_n$. The second dimension describes what each charger is doing at any one time. Because chargers can either charge a bus or not charge, the second dimension contains one charge state for each bus and an additional 'no-charge' state.

The intersection of the i^{th} charge state and j^{th} time index is represented by a node denoted $n_{i,j}$ (see figure 1a). For example, $n_{1,1}$ of figure 1a represents a state where a charger charges Bus 1 at time index t_1.

A complete grid, however, implies that each charger can charge any bus at any time. A bus's schedule is divided into 'route', and 'station' times. A route time corresponds to time periods where a bus leaves the station and provides transit services. During these route times, buses are unable to charge and cannot inhabit a charge state. Therefore, all nodes corresponding to route times must be removed (see figure 1b).

Transitions from one node to the next are called edges (see figure 2) and represent options to either connect, charge, not charge, or disconnect. The type of option depends on which nodes the edge enters and exits. For example, an edge which exits and enters no-charge nodes represents a period of time where the charger begins in a disconnected state, and is not connected thereafter. Hence, the decision was not to charge. When an edge both enters and exits charge nodes, it would, in a similar manner, indicate a to-charge decision. Hence both no-charge to no-charge and charge-to-charge transitions represent *horizontal* shifts in the graph which do not change the effective state of the charger. Conversely, transitions from no-charge to charge, or charge to no-charge nodes respectively represent connect and disconnect decisions which effectively change the charger state (see figure 4). Hence, the bus charge problem can be described in terms of nodes and edges where nodes represent in-station time periods and edges give all possible charge options as shown in figure 3.

Making decisions is encoded in the weight of each edge. The value of each weight is used to represent the number of chargers in the transition. For example, if two chargers were left unused from t_n to t_{n+1}, the corresponding edge would span two no-charge nodes, and have a weight value of two.

Consider a two-charger scenario where buses follow the schedule given in figure 3. A solution where Bus 1 charges from t_1 to t_2 and Bus 2 charges from t_4 to t_5 would be expressed by assigning non-zero weights to the appropriate connect, charge, and disconnect edges as shown in figure 5. Thus, solving the bus charge problem becomes a matter of finding the optimal set of edge weights.

To find the optimal set of weights, the graph must first be encoded in an incidence matrix. An incidence matrix organizes relationships between nodes and edges by describing which edges depart from and connect to which nodes. An incidence matrix A is an nNode $\times$ nEdge matrix where nNode is the number of nodes, and nEdge is the number of edges.

The columns of A describe connections for each edge and the rows give connections for each node. Incoming connections are represented with 1, outgoing connections with -1, and no connection with 0. For example, the graph in figure 6 is represented as:

$$\begin{bmatrix} -1 & 0 & -1 & 1 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix} \tag{1}$$

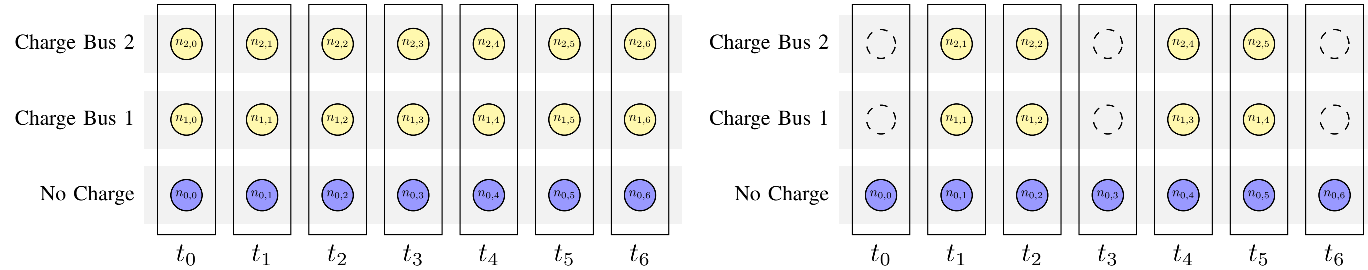
An incidence matrix can be used to find the number of chargers entering and leaving each state. None of the states (charging/non-charging) can create or destroy chargers and so the number of incoming must always equal the number of outgoing chargers. The only exception occurs at *source* and *sink* nodes.

A source node represents the beginning state of all chargers. Because a source state is the first, there are no incoming edges and hence, the net difference between incoming and outgoing chargers, or *the net-flow*, will be minus the number of chargers.

Sink nodes represent the final state, where all chargers enter and finish (see figure 7). Because sinks have no outgoing edges, they maintain a positive net-flow equal to the number of chargers.

Let x be a vector representing the edge weights, A be an adjacency matrix, and c_f be a vector where c_{f_i} gives the net-flow for the i^{th} node. The net-flow for each node can be expressed as

$$Ax = c_f \tag{2}$$



(a) Graph showing buses and timesteps

(b) two-bus scenario from figure 1a where each bus is absent at t_0, t_3, and t_6

Fig. 1: Bus availability represented in a graph

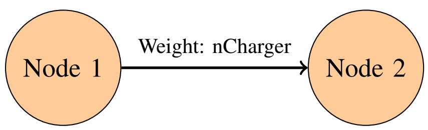


Fig. 2: Node to Node Connection

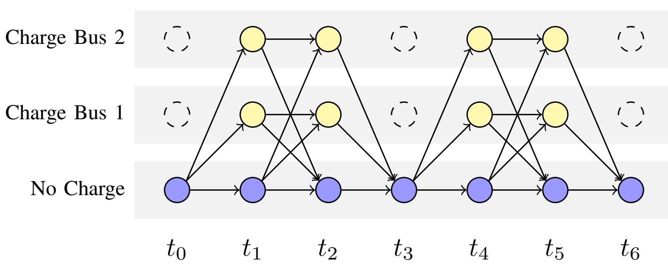


Fig. 3: Complete Problem formulation

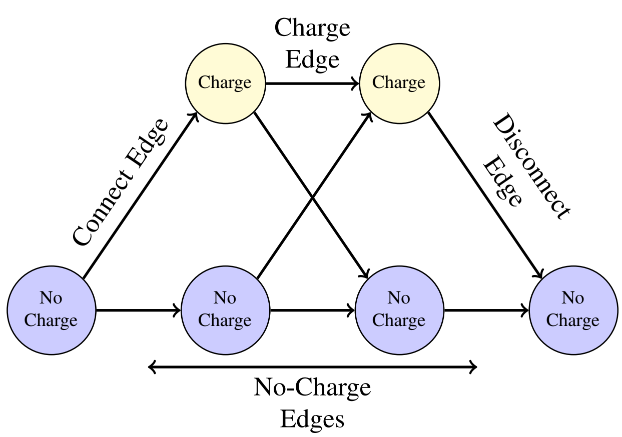


Fig. 4: Connect, Disconnect, and Charge Edges

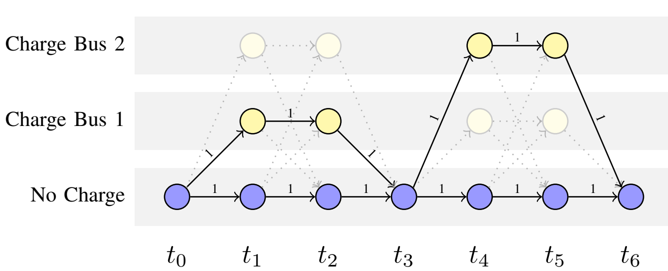


Fig. 5: One solution to a 2-bus 2-charger scenario

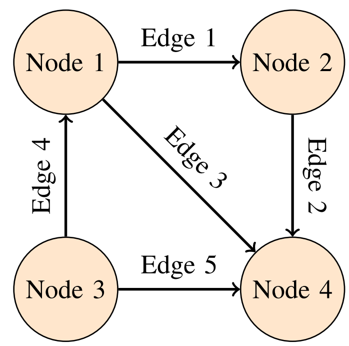


Fig. 6: A generic directed graph consisting of nodes and edges

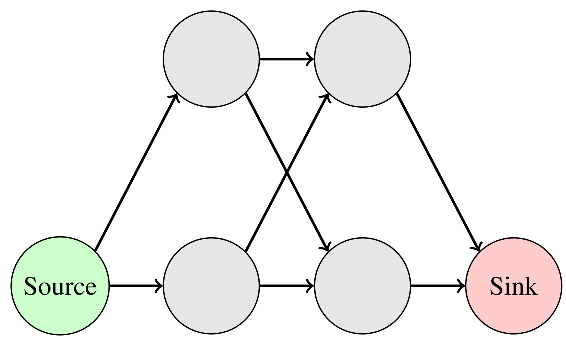


Fig. 7: Network flow illustrating sources and sinks

This expression can be used to constrain the net-flow of each node. c_f must equal zero for all non-source and non-sink elements and source/sink nodes must have net-flows equal to $-$nChargers and nChargers respectively (see equation 3).

$$Ax = \begin{bmatrix} 0 \\ \vdots \\ -\text{nCharger} \\ \vdots \\ 0 \\ \text{nCharger} \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

Flow can also be used to ensure that buses connect to only one charger at a time. Let a charge session, or *group*, be the set of all charge nodes between routes as shown in figure 8.

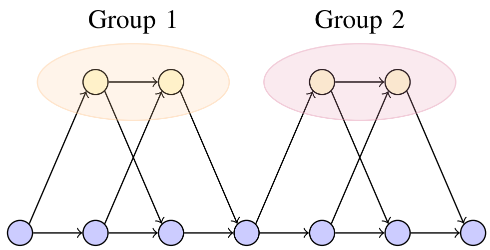


Fig. 8: Example of groups in a network flow graph

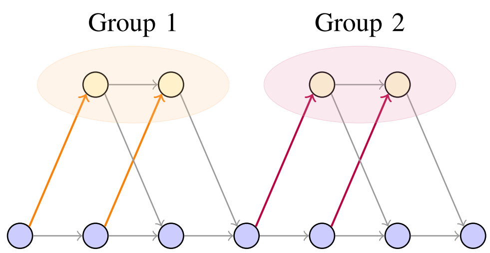


Fig. 9: Incoming Group Edges

The *group flow* is the number of chargers that enter a group and is represented as the sum of all incoming edge weights (see figure 9).

Let B be a nGroup $\times$ nEdge matrix where $B_{i,j}$ is 1 if the j^{th} edge enters the i^{th} group and 0 otherwise. For example, the B matrix corresponding to the graph in figure 10 contains 1 in the 7^{th} and 10^{th} columns for Group 1, and the 12^{th} and 15^{th} columns for group 2 as given in equation 4.

$$B = \begin{bmatrix} 0\,0\,0\,0\,0\,0\,1\,0\,0\,1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,1\,0 \end{bmatrix} \tag{4}$$

Let x be the edge weights as before and c_g be an nGroup $\times$ 1 vector where the i^{th} element gives the group flow for group i. The group flow is then computed as

$$Bx = c_g \tag{5}$$

But the group flow is required to be one at most. This is expressed by the inequality given in equation 6.

$$Bx \leq \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \tag{6}$$

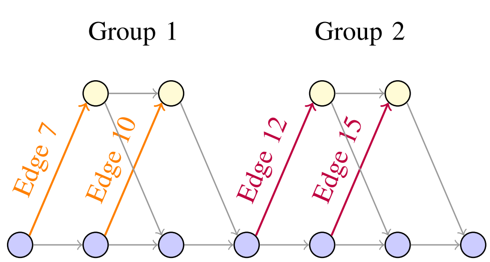


Fig. 10: Connect edge example for groups

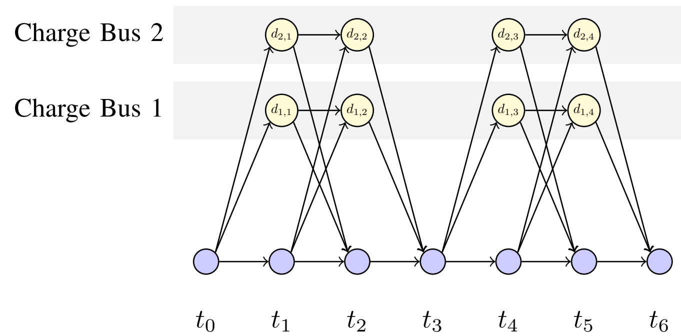


Fig. 11: SOC indicators

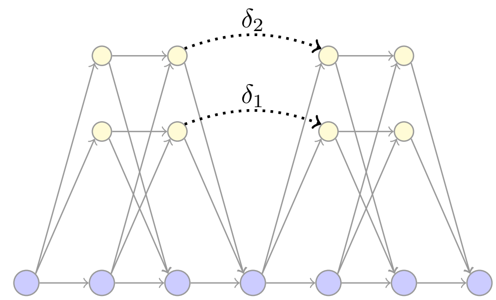


Fig. 12: δ values for routes

IV. Battery State of Charge

Battery state of charge (SOC) also plays a large role in the bus charge problem. As a bus traverses a route, energy is discharged from the battery. If the battery state of charge drops to zero, the bus will power down and become unresponsive. It is therefore important to track battery charge levels when scheduling charge times.

Furthermore, as no charge actions are available while on route, SOC values are only tracked when in the charge station. Because these in-station time periods are also represented by the charge nodes from figure 1b, the two are in one-one correspondence. Consequently, every charge node$_{i,k}$ can be associated with an SOC value, denoted $d_{i,k}$ as shown in figure 11.

Charge level progression between $d_{i,k}$ and $d_{i,k+1}$ is influenced by two factors: discharging on route, and charging. The route discharge, denoted δ, represents the energy drawn from the battery in kWh. When a bus returns from a route, the change in SOC is computed as

$$d_{i,k+1} = d_{i,k} - \delta_i \tag{7}$$

where δ_i is the discharge for Bus i's route as seen in figure 12.

When a charger connects to a bus, the increase or *gain* in $d_{i,k}$ is denoted $g_{i,k}$, where i and k represent the respective bus and outgoing node indices. Figure 13 gives an example where $g_{1,1}$ and $g_{1,3}$ correspond to Bus 1's gain from t_0 to t_1 and t_4 to t_5.

Using a single charge rate however has drawbacks. If the rate is high, buses will charge quickly but the load on the grid will increase. Decreased charge rates will stress the grid less but increase charge time. To address both situations, a method

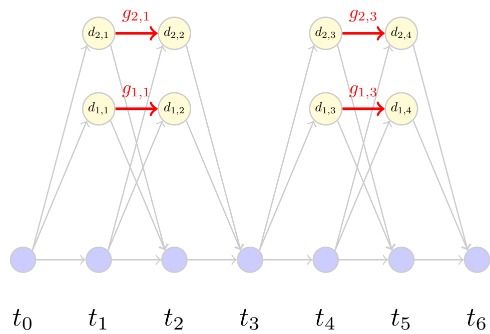


Fig. 13: Depiction of which edges increase SOC for the single rate case

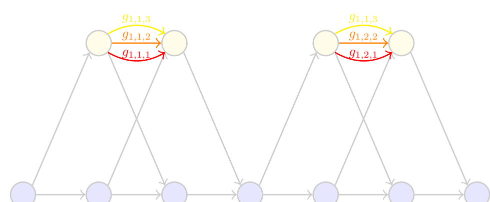


Fig. 14: Multi-Rate Charging

with additional flexibility must be used where both high and low charge rates are available.

Let $g_{i,k,l}$ be the gain, where i and k represent the bus and outgoing node indicies as before and l represents the charge rate index. Each charge rate index corresponds to an edge in the graph. Figure 14 gives an example where there are three rate options. Each rate corresponds to an edge between two charge nodes and together, all three edges provide multiple options for charging. These gains are used to compute succeeding charge levels as

$$d_{i,k+1} = d_{i,k} + \sum_{l} g_{i,k,l}, \tag{8}$$

but because of group and flow constraints, only one charge rate can be active at a time. Therefore, $d_{i,k}$ can be expressed as

$$d_{i,k+1} = d_{i,k} + g_{i,k,l}, \tag{9}$$

where the l^{th} charge edge is active.

$g_{i,k,l}$ is computed using the Constant Current Constant Voltage (CCCV) model as derived in [18] which gives:

$$d_{i,k+1} = \bar{a}_l d_{i,k} - \bar{b}_l M \tag{10}$$

Where $\bar{a}_l \sim (0, 1]$, depends on the charge rate and is experimentally determined, M is the battery charge capacity in kWh, and $\bar{b}_l = \bar{a}_l - 1$. Equations 9 and 10 are used to show that

$$\begin{aligned} & d_{i,k+1} = \bar{a}_l d_{i,k} - \bar{b}_l M \\ \Rightarrow & d_{i,k+1} - d_{i,k} = \bar{a}_l d_{i,k} - \bar{b}_l M - d_{i,k} \\ \Rightarrow & g_{i,k,l} = \bar{a}_l d_{i,k} - \bar{b}_l M - d_{i,k} \\ \Rightarrow & g_{i,k,l} = (\bar{a}_l - 1) d_{i,k} - \bar{b}_l M \end{aligned} \tag{11}$$

The results from equation 11, however, only hold when a charger is connected to a bus, which is represented by a weight of 1 for the edge corresponding to $g_{i,k,l}$. When the weight equals 0, $g_{i,k,l}$ must also equal zero. These two situations can be described using a switching constraint known as the *big M* technique. This technique is used to describe $g_{i,k,l}$ with equation 11 when the transition weight is 1 and $g_{i,k,l} = 0$ when 0.

$$\begin{aligned} & \begin{cases} g_{i,k,l} = d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M & x_{i,k,l} = 1 \\ g_{i,k,l} = 0 & x_{i,k,l} = 0 \end{cases} \\ \Rightarrow & \begin{cases} \begin{matrix} g_{i,k,l} \le d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{i,k,l} \ge d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \end{matrix} & x_{i,k,l} = 1 \\ \begin{matrix} g_{i,k,l} \le 0 \\ g_{i,k,l} \ge 0 \end{matrix} & x_{i,k,l} = 0 \end{cases} \end{aligned} \tag{12}$$

where $x_{i,k,l}$ is the edge weight corresponding to $g_{i,k,l}$. The piecewise function in equation 12 can be rewritten as

$$\begin{aligned} & \begin{cases} \begin{matrix} g_{i,k,l} \le d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{i,k,l} \ge d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \end{matrix} & x_{i,k,l} = 1 \\ \begin{matrix} g_{i,k,l} \le 0 \\ g_{i,k,l} \ge 0 \end{matrix} & x_{i,k,l} = 0 \end{cases} \\ \Rightarrow & \begin{matrix} g_{i,k,l} \le d_{i,k}(\bar{a}_l - 1) - \bar{b}M - M(1 - x_{i,k,l}) \\ g_{i,k,l} \ge d_{i,k}(\bar{a}_l - 1) - \bar{b}M \\ g_{i,k,l} \le 0 + M x_{i,k,l} \\ g_{i,k,l} \ge 0 \end{matrix} \end{aligned} \tag{13}$$

The results of equation 13 obtain a switching effect. When $x_{i,k,l} = 1$, equation 13 becomes

$$\begin{aligned} & g_{i,k,l} \le d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ & g_{i,k,l} \ge d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ & g_{i,k,l} \le M \\ & g_{i,k,l} \ge 0. \end{aligned} \tag{14}$$

The active constraints imply equality for $g_{i,k,l} = (\bar{a}_l - 1) d_{i,k} - \bar{b}_l M$. The inactive constraints imply that $g_{i,k,l}$ is greater then zero, and less then the battery capacity. These constraints are also true, but have no effect on $g_{i,k,l}$. When $x_{i,k,l} = 0$, equation 13 becomes

$$\begin{aligned} & g_{i,k,l} \le d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M - M \\ & g_{i,k,l} \ge d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ & g_{i,k,l} \le 0 \\ & g_{i,k,l} \ge 0. \end{aligned} \tag{15}$$

Where the inactive constraints indicate that $g_{i,k,l}$ is less then some positive value, and greater than a negative value. These constarints have no effect as the active constraints imply equality for $g_{i,k,l} = 0$.

Equation 13 can be expressed in linear form as

$$\begin{aligned} -g_{i,k,l} + d_{i,k}(\bar{a}_l - 1) + x_{i,k,l} &\le M(\bar{b}_l + 1) \\ g_{i,k,l} - d_{i,k}(\bar{a}_l - 1) &\le -\bar{b}_l M \\ g_{i,k,l} - M x_{i,k} &\le 0 \\ -g_{i,k,l} &\le 0. \end{aligned} \tag{16}$$

V. MULTI-GRAPH ADDITIONS

An additional contribution this work offers is the expansion to night vs day charging. During the night, there is one charger

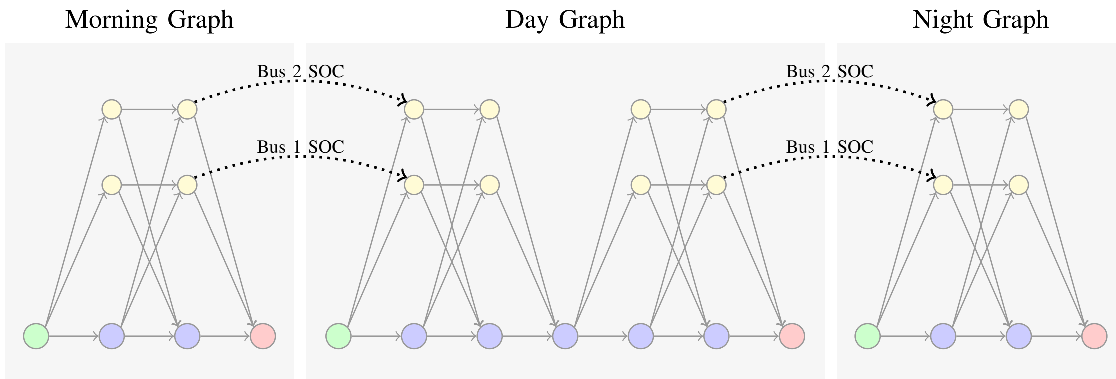


Fig. 15: Night vs Day Graphs

for each bus; each with a single charge rate. During this time, buses are also available to charge at any time. These differences in operations introduce changes to the original graph formation and warrent a separate graph.

Night graphs consider a situation where both the number of buses reflecte the number of chargers and buses are readily available. Note how there are several source and sink nodes in figure 15. When a bus deploys for the day, the available number of charges changes and are reflected in the underlying source and sink constraints.

Changes in the first graph are reflected in the second through use of state of charge variables.

VI. Fiscal Rate Schedule

One objective of this work is to minimize the fiscal cost associated with power use and uses the Rocky Mountain Power schedule 8 billing rates. This billing schedule includes an on-peak power charge, facilities charge, and both on and off peak energy charges.

The facilities charge is computed by calculating the average power over a 15 minute period. The facilities charge is based on the maximum average value over the course of the month. This section of the bill charges \$4.81 per kW. The On-Peak Power Charge is similarly calculated but only includes average values from designated on-peak hours. Rocky Mountain Power charges \$15.73 per kW for this value.

the facilities power can be formulated as a linear set of constraints that include power used at each timestep for charging buses and external loads. This can be expressed as

$$c_i = \sum_j g_{i,j} + p_i$$

Where c_i represnets the

The energy charges are billed per kWh and charge for each unit of energy used. There are two rates: 5.8282¢for energy consumed during on-peak hours, and 2.6316¢for off-peak hours. general introduction with details for demand and consumption charge and how these relate to the end-of-the-month billing.

a. external loads (contribution) b. consumption charge i. total energy in Kwh ii. on-peak vs off-peak iii. constraints for consumption charge c. demand charge i. average power in 15 minute window ii. on-peak vs facilities iii. constraints for on-peak and facilities charges d. total cost breakdown i. Show how Rocky Mountain Power uses these and what the cost weighting is.

VII. Bus Fleet Operations

Overview of bus operations during the day vs the night a. night environment i. one charger per bus ii. slow chargers iii. single rate chargers iv. buses always available b. day environment i. limited number of chargers ii. fast/variable rates iii. limited charging availability c. multiple graphs to incorporate day vs night charging i. show picture to illustrate this ii. show SOC constraints to implement these relationships

VIII. Objective Function

IX. Gurobi & Usage

X. Results

XI. Future Work

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