

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 battery electric buses (BEB). Conversion from diesel and CNG to BEB reduces environmental impact as BEB provide zero emissions and access to renewable energy [14].

These benefits are possible because BEB 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 undesirable for consumers.

One approach to reducing charge costs is to defer upgrades by efficiently managing when and at what rates buses charge. However, developing charge plans must consider a number of factors. All buses must maintain a minimum charge level while adhering to route schedules. When charging, batteries must have sufficient charge time and share a limited number of chargers. All charging must also be done while other services draw power from the grid, acting as uncontrolled loads. The focus of this work is to find an optimal charge schedule which meets these requirements and minimizes fiscal expenses from grid use in the presence of uncontrolled loads. This problem is referred to hereafter as the ‘charge problem’.

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 a graph-based framework for modeling the operations environment. Section IV extends the content of III to account for differences between day and night operations, and Section V incorporates the problem constraints involving battery charge dynamics. Sections VI and VII translate the rate schedule used for billing and into an objective function to minimize. Finally, Sections VIII, IX, and X briefly describe the optimization software used to solve the resulting mixed integer linear program developed in previous sections, presents results, and describes future work.

II. LITERATURE REVIEW

We acknowledge the existence of additional contributions, such as minimizing costs for startup infrastructure [17], and preserving battery lifespan [9]. However, as these are not relevant 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 relevant 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 present circumstances. Methods of this type are computationally efficient, run in real-time, and are adaptable. These techniques generally stem from control theory and manipulate 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 techniques 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 complete foreknowledge of future events and provide globally optimal plans [18],[7]. This class of algorithm requires more computation and is less flexible than reactive or hybrid approaches. However, the solutions 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]. Additionally, power demand generally increases the fiscal cost from a billing perspective. [8] has provided methodology for forecasting 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

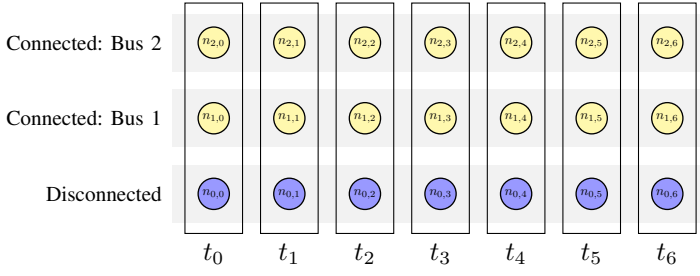


Fig. 1: Graph showing buses and timesteps

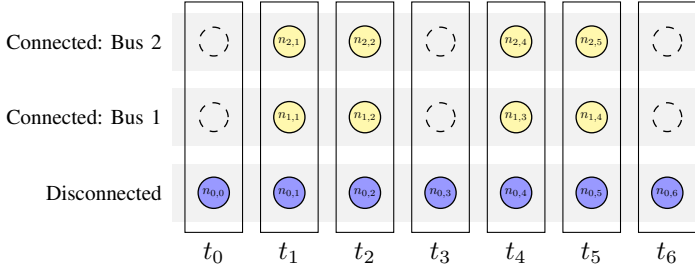


Fig. 2: Bus availability represented in a graph

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 both *when* and *to which* bus a charger should connect suggesting a model with two dimensions. The first dimension characterizes time and is given discretely in a left to right fashion. The second dimension encodes the charger state and extends vertically as seen in figure 1. The charger may occupy one of several states. It may be connected to one of the N buses, or it may be unconnected, giving a total of $N + 1$ charge states. The 2-D representation is encoded as a grid where the intersection of charge states and time indices is represented by a node, denoted $n_{i,j}$ which represents the i^{th} charge state at the j^{th} time index (see figure 1).

A complete grid, however, implies that buses are always available to charge. This is not always the case as buses cannot charge when providing transit services. To reflect this constraint, the presence of nodes is used to denote a bus's availability for charging and nodes are removed during times where a bus provides transit services (see figure 2).

Transitions from one node to the next are called edges (see figure 3) and represent decisions to either connect, charge, not charge, or disconnect. The decision an edge represents is determined by the nodes on either end. For example, the edge from $n_{0,0}$ to $n_{0,1}$ in figure 5 represents a period where chargers are idle, resulting in a no-charge decision. This occurs because both $n_{0,0}$ and $n_{0,1}$ represent a disconnected charge state. Similarly, the edge between $n_{1,1}$ and $n_{1,2}$ indicates a to-charge decision as both $n_{1,1}$ and $n_{1,2}$ represent states where a charger is connected. Both to-charge and no-charge decisions

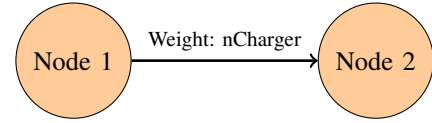


Fig. 3: Node to Node Connection

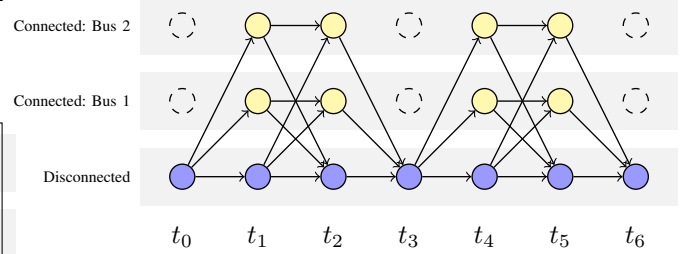


Fig. 4: Graph-based model of the complete decision-space

are represented by *horizontal* transitions in the graph and do not change the effective charger state.

Conversely, diagonal transitions represent effective state changes where a charger either connects to or disconnects from a bus. One such example from figure 5 includes the edge from $n_{0,0}$ to $n_{1,1}$. This edge represents an interval where a charger is disconnected at t_0 and connected at t_1 , implying a 'to-connect' decision. The same logic applies in reverse for the edge between $n_{1,2}$ and $n_{0,3}$. Hence, the bus charge problem can be described in terms of nodes and edges where nodes represent connectable time instances and edges encode *potential* decisions. Figure 4 shows the graph that represents the decision space of the scenario given in figure 2.

Schedule selection is represented by selecting edges to determine a path through the graph. Edge selection is indicated by a binary edge weight. A zero-valued weight indicates an unused, edge whereas a unit-valued weight represents an edge occupied by a charger.

Multiple chargers can be expressed in terms of multiple corresponding graphs. However, this would significantly increase the number of edges and nodes. Multiple graphs can be expressed in a joint form by superimposing each binary graph for form a composite representation. The edge weight values connecting to bus nodes remain binary as only one charger can connect at a time. Edges representing unconnected chargers however become an integer with a maximum value equal to the number of chargers.

Consider a two-charger scenario using the graph in figure 4. A solution where one charger is connected to Bus 1 from t_1 to t_2 and to Bus 2 from t_4 to t_5 would be expressed by assigning unit weights to the appropriate connect, charge, and disconnect edges. The second charger remains idle as illustrated by the active edges along the bottom row of charger states (see figure 6). Thus, solving the bus charge problem becomes a matter of finding the optimal set of edge weights.

The bus charge problem aims to minimize the fiscal expense from charging while meeting the operational constraints of a transit system. The graph encodes a subset of these constraints

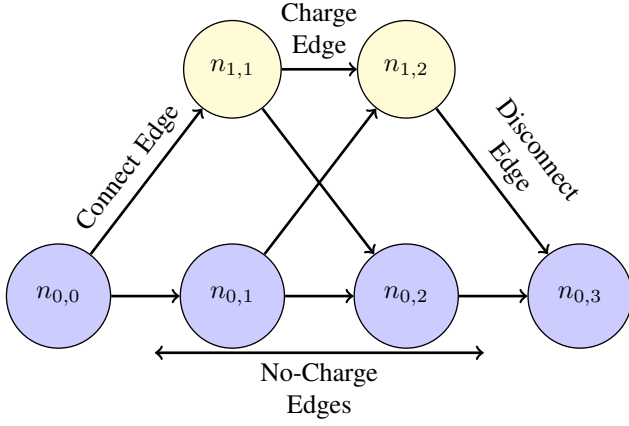


Fig. 5: Connect, Disconnect, and Charge Edges

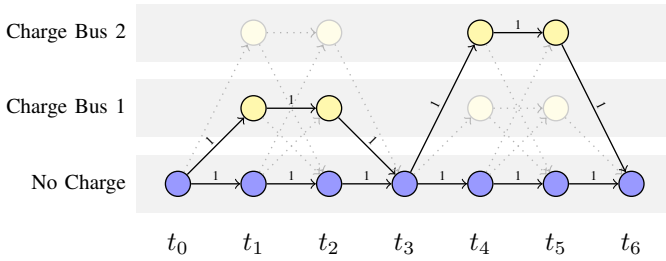


Fig. 6: One solution to a 2-bus 2-charger scenario

and can be expressed in linear form

$$Ax = c_f, \quad (1)$$

where A is the graph incidence matrix, x is an $n\text{Edge} \times 1$ vector of edge weights, and c_f is $n\text{Node} \times 1$ and equals the difference between incoming and outgoing edge weights, or *flow*.

An incidence matrix organizes relationships between nodes and edges by describing which edges leave and enter which nodes. The matrix A is an $n\text{Node} \times n\text{Edge}$ matrix and expresses incoming connections between the i^{th} node and j^{th} edge as $A_{i,j} = 1$. Similarly, outgoing connections are given with $A_{i,j} = -1$, and no connection with $A_{i,j} = 0$. For example, the graph in figure 7 is represented as:

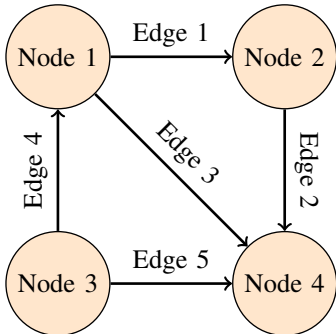


Fig. 7: A generic directed graph consisting of nodes and edges

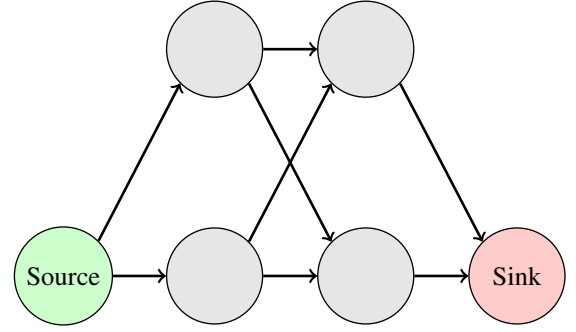


Fig. 8: Network flow illustrating sources and sinks

$$\begin{bmatrix} -1 & 0 & -1 & 1 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix} \quad (2)$$

The difference between the number of chargers entering and leaving, or the *net-flow*, can be expressed in terms of A as seen in equation 1. Because the number of chargers must be conserved, the number of incoming and outgoing chargers must be equal. This is expressed in linear form as $a_i^T x = 0$, where a_i is the i^{th} row of A . The only exceptions occur at *source* and *sink* nodes.

A source node represents the beginning state for all chargers. Because edges originate here, there are no incoming edges and the net-flow will be minus the number of chargers. This is described in linear form as $a_i^T x = -n\text{Charger}$.

Sink nodes represent the final state, where all edges terminate (see figure 8). Because sinks have no outgoing edges, they maintain a positive net-flow equal to the number of chargers and are expressed as $a_i^T x = n\text{Charger}$.

Therefore, the *flow constraints* require that c_f be equal to zero for all non-source and non-sink nodes as seen in equation 3.

$$Ax = \begin{bmatrix} 0 \\ \vdots \\ -n\text{Charger} \\ \vdots \\ 0 \\ n\text{Charger} \\ \vdots \\ 0 \end{bmatrix} \quad (3)$$

Flow can also be used to ensure that chargers connect to a given bus only once during each visit to the station. A single charge period is desired because multiple reconnects, or charger thrashing, is inconvenient for station staff.

Define a charge group as the set of all nodes for a given bus corresponding to one station visit as shown in figure 9. 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 10).

Denote the $n\text{Group} \times n\text{Edge}$ group incidence matrix as B , where $B_{i,j}$ is 1 if the j^{th} edge enters the i^{th} group and 0 otherwise. For example, the group incidence matrix

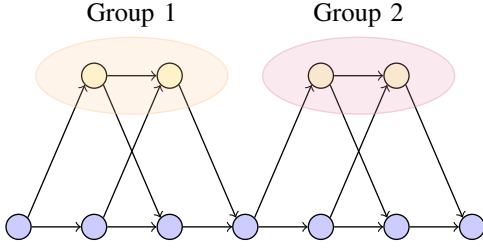


Fig. 9: Example of groups in a network flow graph

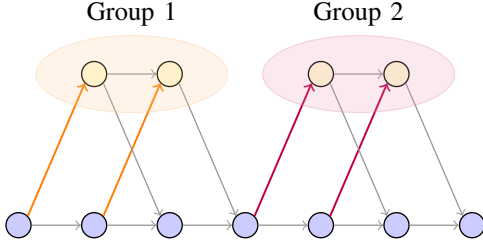


Fig. 10: Incoming Group Edges

corresponding to the graph in figure 11 contains 1 in the 7th and 10th columns for Group 1, and the 12th and 15th columns for group 2 as given in equation 4.

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (4)$$

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

$$Bx = c_g \quad (5)$$

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

$$Bx \leq \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}, \quad (6)$$

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

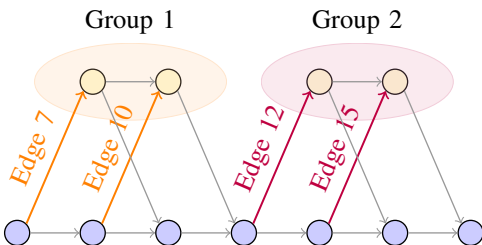


Fig. 11: Connect edge example for groups

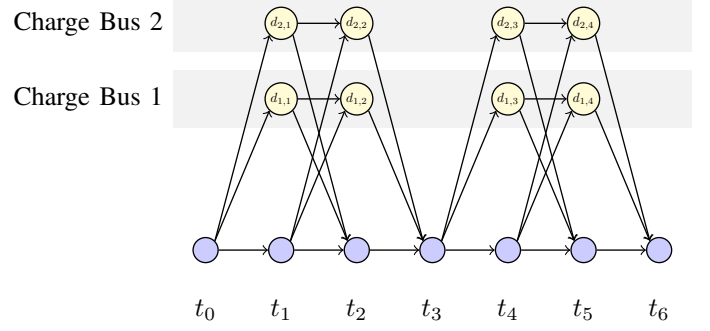
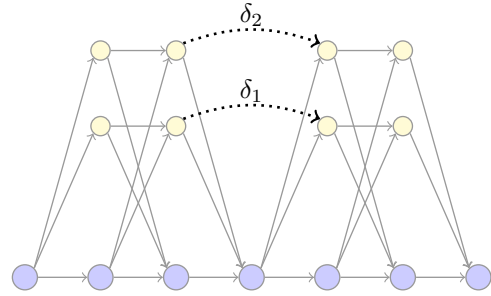


Fig. 12: SOC indicators

Fig. 13: δ values for routes

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 ??, the two are in one-one correspondence. Consequently, every charge node $d_{i,k}$ can be associated with an SOC value, denoted $d_{i,k}$ as shown in figure 12.

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

$$d_{i,k+1} = d_{i,k} - \delta_i \quad (7)$$

where δ_i is the discharge for Bus i 's route as seen in figure 13.

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 14 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 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 indices as before and l represents the

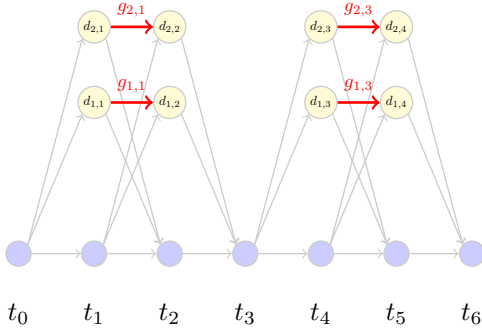


Fig. 14: Depiction of which edges increase SOC for the single rate case

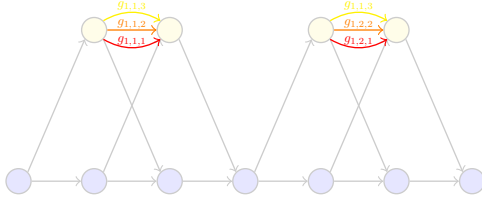


Fig. 15: Multi-Rate Charging

charge rate index. Each charge rate index corresponds to an edge in the graph. Figure 15 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

$$d_{i,k+1} = d_{i,k} + \sum_l g_{i,k,l}, \quad (8)$$

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

$$d_{i,k+1} = d_{i,k} + g_{i,k,l}, \quad (9)$$

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:

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

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

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

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.

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

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

$$\begin{aligned} &\begin{cases} g_{i,k,l} \leq d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M & x_{i,k,l} = 1 \\ g_{i,k,l} \geq d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M & x_{i,k,l} = 1 \\ g_{i,k,l} \leq 0 & x_{i,k,l} = 0 \\ g_{i,k,l} \geq 0 & x_{i,k,l} = 0 \end{cases} \\ \Rightarrow &\begin{cases} g_{i,k,l} \leq d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M - M(1 - x_{i,k,l}) \\ g_{i,k,l} \geq d_{i,k}(\bar{a}_l - 1) - \bar{b}_l M \\ g_{i,k,l} \leq 0 + Mx_{i,k,l} \\ g_{i,k,l} \geq 0 \end{cases} \end{aligned} \quad (13)$$

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

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

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

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

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

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

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 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.

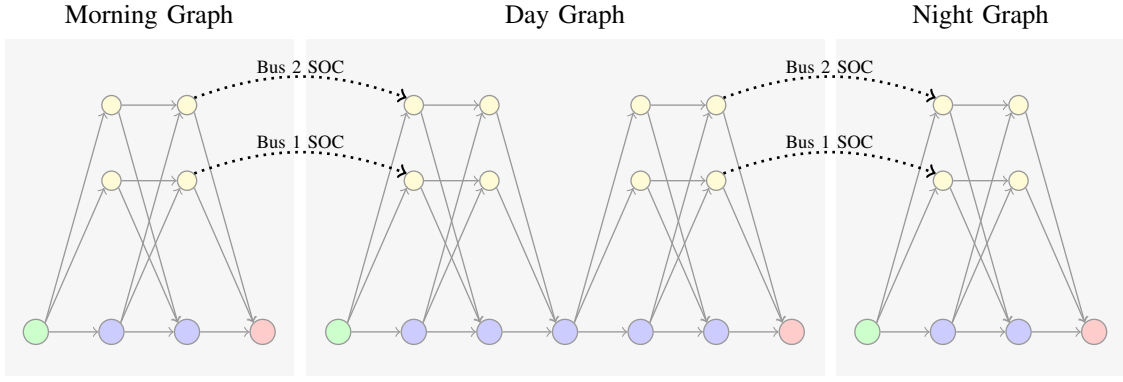


Fig. 16: Night vs Day Graphs

Night graphs consider a situation where both the number of buses reflect the number of chargers and buses are readily available. Note how there are several source and sink nodes in figure 16. 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 represents 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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