An Energy Transmission and Distribution Network Using Electric Vehicles

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***Abstract*—Vehicle-to-grid provides a viable approach that feeds the battery energy stored in electric vehicles (EVs) back to the power grid. Meanwhile, since EVs are mobile, the energy in EVs can be easily transported from one place to another. Based on these two observations, we introduce a novel concept called *EV energy network* for energy transmission and distribution using EVs. We present a concrete example to illustrate the usage of an EV energy network, and then study the optimization problem of how to deploy energy routers in an EV energy network. We prove that the problem is NP-hard and develop a greedy heuristic solution. Simulations using real-world data shows that our method is efficient.**

I. INTRODUCTION

The transportation industry is the second biggest greenhouse gas producer in the world [1]. Many countries have been developing electric vehicles to reduce global warming and greenhouse gases emission. As electric vehicles (EVs) have batteries that can store energy, they can be used to store energy and feed energy back to the grid as needed: this is called vehicle-to-grid (V2G) [2].

In V2G, a large number of EVs can become a large energy storage system. For instance, if all light vehicles in the United States become EVs, their power capacity is 24 times that of the entire electric generation system [4]. But at the same time, EVs can move from one place to another place, and transport energy from place to place. Inspired by the above two observations, we present an EV-based energy network, termed *EV energy network* for energy transportation in this paper. Our main contributions are as follows.

- We introduce the concept of EV energy network. It consists of EVs, EV charge stations and an energy transportation network. It can transmit energy by EVs and distribute energy from renewable energy sources to charge station.
- We design a concrete example to illustrate an EV energy network. It consists of an electric bus company in one city. Buses are used to transmit and distribute energy from renewable energy sources to charge stations.
- We formulate an optimization problem with the objective of minimizing the number of charge stations while providing full coverage for all bus lines and minimizing the loss of transmission energy in an EV energy network. We prove that the problem is NP-hard, and present a greedy algorithm based on a bipartite graph to solve it. Simulation using Manhattan bus lines in New York city demonstrates that our algorithm is efficient.

The paper is organized as follows. We introduce the concept of an EV energy network and some applications in Section II. We formulate the the charge-station placement problem in Section III, and provide a heuristic solution in Section IV. Section V presents simulation results. Finally, Section VI concludes this paper.

II. PROBLEM DESCRIPTION

One of the main causes of global warming, greenhouse effect and climate change is too much CO_2 emission. The power and energy industry is responsible for 40% of the global CO_2 emission [1]. Therefore, renewable energy, mainly solar and wind, will become more and more attractive. The global solar power could reach 25 GWh by 2020, according to analyst Emerging Energy Research (EER) [6]. However, as renewable power is unstable and intermittent, it is not easy to connected it to the grid [8], [9]. Wide deployment of electric cars presents another promise to reduce CO_2 emission. For instance, United States will have one million electric cars and plug-in hybrids by 2015 [3]. These large number of EVs, however, require a large amount of energy, posing a potential detrimental impact on the power grid [10]. EV energy networks that use EVs to transmit and distribute energy from renewable energy sources to EV charging systems can provide a good solution to the above two problems simultaneously.

A. The EV energy network

The basic idea of an EV energy network is that EVs transport energy from renewable energy (solar or wind) plants to users that need power (e.g., charging stations and houses). Fig. 1 shows a schematic diagram of an EV energy network. The lower layer is the EV transport network. It consists of three main parts: energy generation, energy transportation and energy consumption. Energy generation includes renewable energy plants. Energy transportation is composed of EVs and EV charge stations. Energy consumption is composed of users that need energy (e.g., houses and charge stations). The upper layer is an EV energy network similar to a data communication network.

B. Applications for EV energy network

An EV energy network is an energy transmission system that allows the transport of energy from its place of gener-

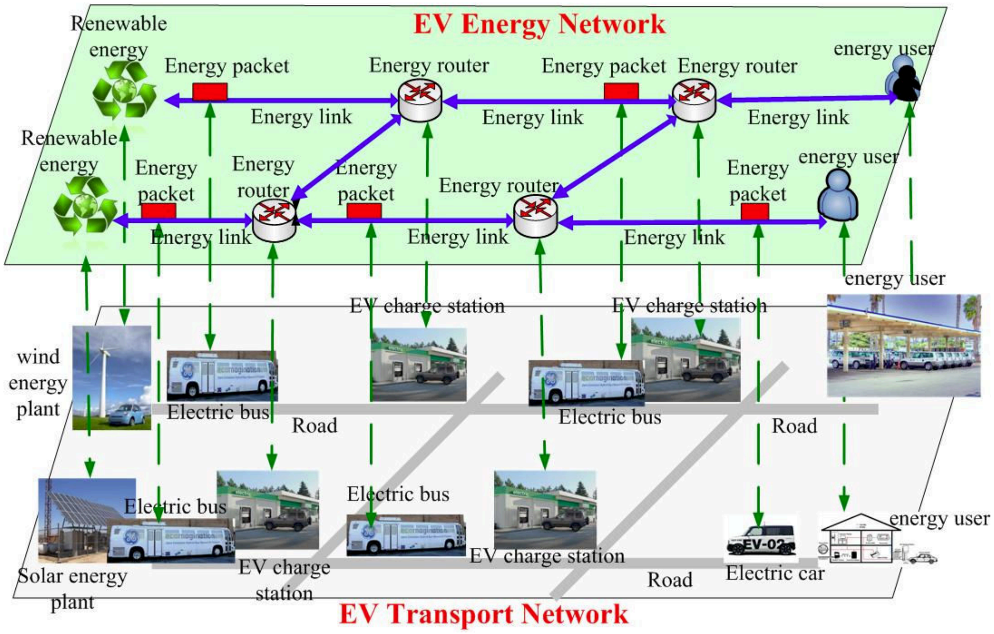

Fig. 1. Schematic of EV energy network

ation to a location where it is used to perform useful work without the use of power lines. It has many applications, including power dispatch between cities, power transmission from renewable energy sources to end users such as EV charge stations.

We illustrate an EV energy network through a simple application. It is an electric bus company in one city. All buses in the company are electric buses. The company accesses solar energy stations placed in rural areas to generate power to charge electric buses. Most of the charge stations are inside the city to charge electric buses. The EV energy network is responsible for transporting energy from the rural areas to charge stations in the city.

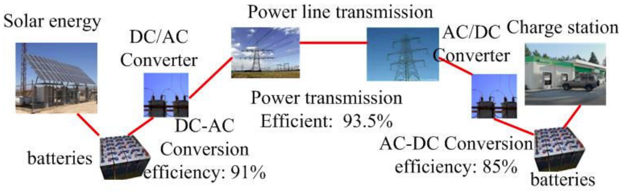

Fig. 2. Energy transmission through power grid.

Before we describe the approach via the EV energy network, we present an alternate way to transport energy, namely transmitting energy through grid as shown in Fig. 2. The process consists of three steps. The first step is to convert DC power created by the solar panels into grid-ready AC power. This incurs a loss of about 10% of the total power [11], [22], [23]. The second step is transmission by power lines, which incurs a loss of about 6.5% [13]. The third step is to convert AC power to DC power for charging rechargeable batteries in charge stations and its efficiency is 85% [14]. The total power loss of the process is about 27.8%.

The approach to transmitting energy through an EV energy network is shown in Fig. 3. The process also consists of three steps. The first step is to charge EVs using DC energy and its efficiency is 95% [15]. The second step is energy transportation using EVs from solar energy stations to charge stations. The main source of loss is battery discharge that loses 0.13% per day [16], [17], [19], [21]. The third step is to charge batteries in charge stations from EVs and it incurs a loss about 5% [15]. The total power loss of the process is less than 10%. From the above analysis, it is clear that the approach via an EV energy network is more efficient than the first approach via power lines.

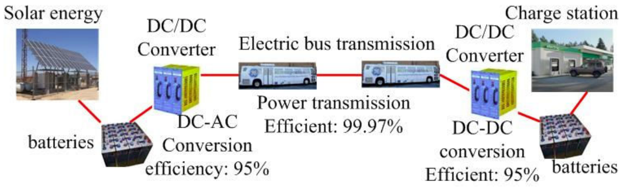

Fig. 3. Energy transmission through an EV energy network.

III. PROBLEM FORMULATION

To build an energy network to support electric buses, the first problem we face is where to set up the charge stations and how many charge stations are needed. The simplest solution is to set up charge stations at all bus stops. This, however, may incur prohibitive costs. To reduce the investment, we should build the minimum number of charging stations while meeting the needs of all electric buses. The second problem is to how to reduce the energy loss when energy is transferred from the renewable energy sources to charge stations, as each charge and discharge process incurs energy loss. We next describe the charge station placement problem formally.

Let $S = \{s_1, ..., s_n\}$ denote the set of bus stops. Let $L = \{l_1, ..., l_m\}$ denote the set of bus lines. Each bus line contains a set of bus stops. Let $D = \{d_1, ..., d_l\}$ denote

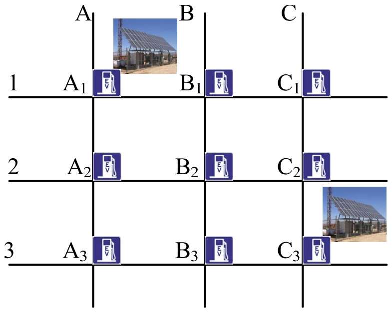

Fig. 4. Schematic diagram of bus lines

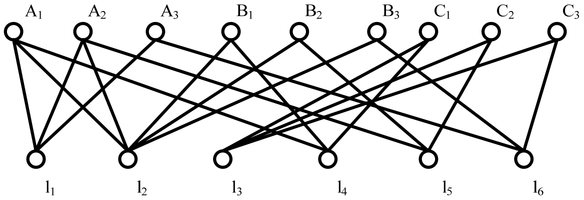

Fig. 5. the bipartite graph for bus lines and bus stops

the set of renewable energy sites. For simplicity, assume that renewable energy sites are located at bus stops. Then $D \subseteq S$. Fig. 4 shows an example. There is one bus stop at the intersection of two streets, denoted as A_i, B_i or C_i, $i = 1, 2, 3$. Assume six bus lines: $l_1 : (A_1, A_2, A_3), l_2 : (B_1, A_1, A_2, B_2, B_3), l_3 : (C_1, C_2, C_3), l_4 : (A_1, B_1, C_1), l_5 : (A_2, B_2, C_2)$, and $l_6 : A_3 - B_3 - C_3$. There are two renewable energy sources, A_1 and C_3.

We define a bipartite graph $G = \{S, L, E\}$, where the two vertex sets S and L are the sets of bus stops and bus lines, respectively, the edge set $E \in S \times L$ represents the relationship between the two vertex sets. In particular, an edge $(s_i, l_j) \in E$ connects bus stop $s_i \in S$ and bus line $l_j \in L$ if the bus stop is along the bus line. Let L_s denote the set of bus lines that passes bus stop s. That is, $L_s = \{l \mid (s, l) \in E\}$. For ease of exposition, we also say L_s is the set of bus lines that are *covered* by bus stop s. Fig. 5 plots the bipartite graph corresponding to the example in Fig. 4.

Charge stations storage and forward energy: energy from a bus can be deposited at a charge station, which is used to charge another bus. We assume charge stations are placed at bus stops. Recall that L_s denotes the set of bus lines that passes bus stop s. When a charge station is placed at bus stop s, it can be used by all the bus lines in L_s. For ease of exposition, we also say L_s is the set of bus lines that are *covered* by charge station s.

A. Coverage problem

The first problem we discuss is how to find the smallest number of charge stations to cover all the bus lines, referred to as the **charge station cover (CSC)** problem. Let $C \subseteq S$ denote the set of charge stations. Then the CSC problem is

$$\min_{C \subseteq S} |C| \tag{1}$$

$$\text{Subject to} \bigcup_{s \in C} L_s = L.$$

In the example in Fig. 4, the CSC problem is equivalent to choosing the minimum number of upper-level nodes to cover all of the lower-level nodes. It is easy to see that the CSC problem is equivalent to the minimum set cover problem, and hence is NP-hard.

B. Energy loss

The second problem is to how to reduce the energy loss when energy is transferred from the renewable energy sources to the charge stations. Since each charge-discharge process incurs energy loss, we would like to find the shortest route from renewable energy sources to each charge station in order to reduce energy loss.

For a renewable energy source $d \in D$ and a charge station $s \in C$, let $P(d, c)$ denote the set of *energy transfer paths* from d to c in the bipartite graph G where all the intermediate bus stops are charge stations. For convenience, let $P(d, c) = \emptyset$ if no such path exists. Then each path in $P(d, c)$ represents a path to transfer energy from renewable energy source d to charge station c. Specifically, suppose one path is $(d, l_{[1]}, c_{[1]}, l_{[2]}, c_{[2]} \ldots, c_{[k]}, c)$. Then it represents that energy from renewable energy source d can be transferred through charge stations $c_{[1]}, c_{[2]}, \ldots, c_{[k]}$, and eventually to charge station c (specifically, buses running on bus line $l_{[1]}$ are charged by d and discharge at $c_{[1]}$, where the energy is picked up by buses running on $l_{[2]}$, which in turn discharge at $c_{[2]}$, and so on). The energy transfer path of a charge station c is defined to be the shortest path from any of the renewable energy sources to c, which represents a path to transfer energy from a renewable energy source to c with the minimum percentage of energy loss.

We next define energy loss formally. For simplicity, here we only consider energy loss due to EV charge-discharge. Let β denote the efficiency of one-time energy charge and discharge for an EV. In the example in Fig. 3, $\beta = 0.95 \times 0.95 = 0.90$. Let k_c denote the number of bus lines in the energy transfer path of charge station c. Then the percentage of energy loss for c is $1 - \beta^{k_c}$. As an example, suppose the set of charge stations $C = \{A_1, C_2, C_3\}$ in Fig. 4. For charge stations A_1 and C_3, since they are also renewable energy sources and do not require buses to transfer energy to them, their energy loss is 0. For charge station C_2, its energy transfer path is $\{C_3, l_3, C_2\}$, with energy loss of $1 - \beta$.

IV. PROBLEM SOLUTION

In Section II, we have proved that the CSC problem is NP-hard. In this section, we present a heuristic algorithm to solve the CSC problem. This algorithm places a set charge stations to cover all bus lines, and aims at using a small number of charge stations and reducing energy loss.

The main idea of the algorithm is as follows. Initially, let set of charge stations, C, be an empty set. At each step we construct a bipartite graph $G' = (S', L', E')$ where L' represents the yet to be covered bus lines and S' the bus stops associated with these lines that have not been chosen to be transfer stations (initially, $L' = L$ and $S' = S$). Let T be the

Algorithm 1: Charge Station Placement Algorithm

```
$C = \emptyset$;
$L' = L$;
$S' = S$ ;
construct bipartite graph $G'$ that connects $S'$ and $L'$ ;
$T = D$;
$i = 0$;
while $L' \neq \emptyset$ do
    Select the largest degree node $s \in T$;
    while $T \neq \emptyset$ and $L' \neq \emptyset$ do
        $C = C \cup \{s\}$;
        $S' = S' \setminus \{s\}$;
        $L' = L' \setminus L_s$;
        construct bipartite graph $G'$ that connects $S'$ and $L'$;
        $T = T \setminus \{s\}$;
    $i = i + 1$;
    Update $T \subseteq S$ to be nodes that are $i + 1$ hops away from nodes in $D$;
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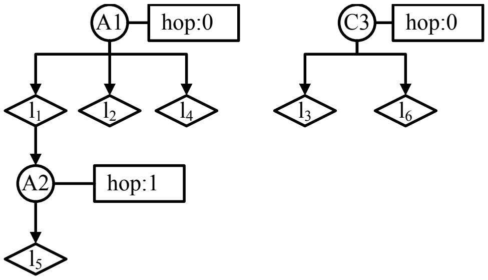

Fig. 6. Illustration of the proposed algorithm for the example shown in Fig. 5.

set of potential charge stations. To reduce energy loss, we first add all the renewable energy sources to T. Among the nodes in T, we select the node with the largest degree (the degree refers to the degree in G') as the charge station, and remove all the bus lines that are covered by this charge station from the graph. We then This step is repeated until all bus lines are covered or T is empty. If T is empty, we add the bus stops that are one hop away from the renewable energy sources to T, and repeat the above process. If T becomes empty and some bus lines remain to be covered, we add the bus stops that are one hop away from the renewable energy sources to T. The above procedure continues until all bus lines are covered. The algorithm is summarized in Algorithm 1.

We next illustrate our proposed algorithm using the example in Fig. 5. The process is shown in Fig. 6. We first add renewable energy sources, A_1 and C_3, to T. The degree of A_1 is three and the degree of C_3 is two (see Fig.5). We first select A_1 as charge station. The bus lines that node A_1 covers are l_1, l_2 and l_4. We remove A_1 from set T and remove l_1, l_2, l_4 from L'. After that, we select C_3 as charge station and remove the bus lines that it covers (i.e., l_3 and l_6) from L'. Afterward, since T is empty and there remains one bus line (i.e., l_5) to be covered, we add bus stops that are one hop away from the renewable energy sources to T. Namely, we add $A_2, A_3, B_1, B_2, B_3, C_1, C_2$ to T. Now the degree of A_2, B_2, C_2 is 1 and the degree of the other nodes is 0. We arbitrarily select A_2 as charge station, which covers l_5. Then all the bus lines are covered and the algorithm terminates.

V. SIMULATION AND ANALYSIS

In this section, we evaluate the performance of our proposed charge station placement algorithm using real-world data. In particular, our evaluation is based on the Manhattan bus map in New York city [31]. There are 37 bus lines and about 400 bus stops in Manhattan. We select bus stops that serve at least two bus lines, and then remove repeated and isolated bus stops. After the above precess, we get 159 bus stops. The metrics that we use to evaluate our algorithms are the number of charge stations and the average percentage of energy loss (i.e., to transmit energy from the renewable energy sources to the charge stations, see Section III-B. In the simulation, we use $\beta = 0.90$). We vary the number of renewable energy sources from 1 to 15. For each setting, we generated 100 settings by randomly placing renewable energy sources using independent random seeds and obtain 95% confidence intervals.

We implement both our proposed algorithm in Malab7.0, and compare it performance to a baseline algorithm that randomly choose charge stations. Specifically, it differs from our algorithm in that it randomly select a sequence of charge stations, denoted as C_1, to cover all the bus lines. Then for each charge station in $s \in C_1$, it finds the shortest path from the renewable energy sources to s, and add all the nodes along the shortest path as charge stations (so that we can find a energy transfer path from the renewable energy sources to s).

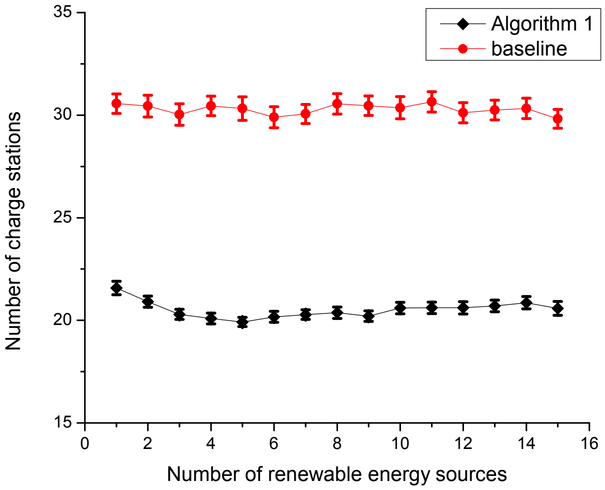

Fig. 7. The number of charge stations under our proposed algorithm and the baseline algorithm.

Fig. 7 plots the number of charge stations under the two algorithms. When using our proposed algorithm, the average number of charge stations when varying the number of renewable energy sources is below 22.5, significantly lower than that under the baseline scheme. Fig. 8 plots the average percentage of energy loss under the two algorithms. The average energy

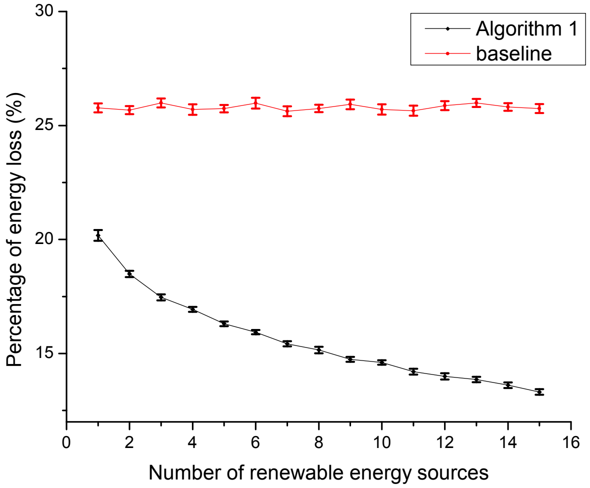

Fig. 8. Percentage of energy loss under our proposed algorithm and the baseline algorithm.

loss of our proposed algorithm is 20.1% when there is only one renewable energy station, and decreases when increasing the number of renewable energy sources. For all the settings, our algorithm outperforms the baseline algorithm. In summary, our proposed algorithm is much more efficient than the baseline algorithm: it requires less charge stations and incurs less energy losses.

VI. CONCLUSIONS

Energy is one of the most precious resources in the world. Researchers have proposed various approaches to either reduce energy consumption [20], [7] or efficiently and securely utilize energy [12], [24], [30], [18], [5], [28], [27], [26], [25], [29]. In this paper, we proposed a novel concept called EV energy network, for energy transmission and distribution using EVs. We described an example application of EV energy network, and studied how to deploy charge stations in an EV energy network. We first proved that it is NP-hard problem, and then developed a heuristic algorithm to solve it. Simulation results using real-world data demonstrate that our algorithm significantly outperforms a baseline scheme.

VII. ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China (No. 61170164, No. 60932003), Shanghai Municipal Natural Science Foundation (No. 09ZR1414900), National 242 Information Security Plan of China (No. 2011A004), Opening Project of Key Lab of Information Network Security of Ministry of Public Security (No. C11608), and Binghamton University academic program and faculty development fund.

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