Energy Scheduling and Allocation in Electric Vehicle Energy Distribution Networks

Ping Yi*, Ting Zhu†, Guangyu Lin*, Xiuchen Jiang*, Guojie Li*, Liangqi Si‡, Miroslav M. Begovic‡
*School of Electronic, Information and Electrical Engineering , Shanghai Jiao Tong University, Shanghai, 200240, China
†Department of Computer Science, Binghamton University, Binghamton, NY, 13905 , USA
‡School of Electrical and Computer Engineering, Georgia Institute of Technology, 30332, Georgia, USA

***Abstract*—The energy storage of Electric Vehicles (EVs) can be utilized by Smart Grid through Vehicle-to-Grid (V2G) that allows EVs to feed energy stored in their batteries back to the grid as needed. Combining V2G and the mobility of vehicles, EVs can provide a natural energy transmission system called EV energy network. The main idea of this paper focus on how to schedule and allocate energy from energy sources to places where energy is needed. The features of energy route in EV energy network are analyzed and a greedy algorithm based on the hypergraph is presented. Simulations using real-world transporting data in Manhattan and the Pioneer Valley Transit Authority(PVTA). Simulations show that this method is efficient.**

I. Introduction

V2G allows the electricity to flow from EVs to power lines [1]. EVs equipped with batteries can pack a lot of power and may be regarded as a large-scale distributed 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 [2]. In the meanwhile, EVs are movable. Combining V2G and mobility of the vehicles, EVs can transmit energy from one place to another.

In the previous work, we present *EV energy network* that uses EVs to transmit and distribute energy [4]. And we study the optimization problem of how to deploy energy routers which can receive and forward energy in an EV energy network. A greedy algorithm is presented to minimize 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.

In this paper, the main idea in this paper is how to schedule energy from the energy sources to charge stations. The main contributions are as follows.

- The features of the EV energy network. The EV energy network is comprised of EVs and EV charge stations, in order to transmit and distribute energy from renewable energy plants to energy users. An application of the EV energy network in the electric bus system is described. The EV energy network is used to efficiently distribute energy from renewable energy plants to all the buses in the system, because buses provide free ride to all the energy they carried. It is similar to the communication network but it is different from the communication network.
- Develop a greedy algorithms to schedule energy from energy sources to charge stations with less energy loss. A hypergraph model is introduced to analyze the EV energy network, and an optimization problem is discussed to minimize the hops of energy route while transmit energy from energy sources to all charge stations.
- Test the algorithm by real-world transporting data, which is transporting map date using Manhattan bus lines in New York city and the bus map of the Pioneer Valley Transit Authority(PVTA).

The rest of the paper is organized as follows. The problem about how to schedule and transmit energy with minimal cost in EV energy network is introduced in Section II. The problem is formulated in Section III and a solution is provided in Section IV. Section V presents the simulations and analysis. Section VI compares the EV energy network with the communication network and discusses the features of the EV energy network. Section VII concludes the paper.

II. Problem Description

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 the so-called Vehicle-to-Grid (V2G) [1].

Electric vehicles do not only store a lot of energy in their batteries [2], but also transport these energy with the movement of EVs. In our previous work, EV energy network is presented to transmit and distribute energy from energy sources to energy users [4]. The paper describes the concept of the EV energy network and presents an algorithm to solve the problem how to deploy charge stations namely energy routers in the EV energy network.

In addition, another key problem is how to schedule and transmit energy with minimal cost in the EV energy network. There are two points in this problem. One is energy distribution and schedule. In EV energy network, energy sources such as solar plants or wind plants have limited energy generation everyday. Energy users like charge stations have different energy consumption in everyday. There are many energy sources with different energy generation as well as many charge stations with different energy demand. It is an optimization problem of how to schedule these energy to fulfill the need from all energy users.

The other point is how to select the route to transmit energy from energy sources to energy users. The energy loss is about 10% [4] when energy is transmitted in the EV energy network. Therefore, finding the shortest route from energy sources to energy users is necessary for the minimization of the energy loss.

III. Problem Formulation

To clearly illustrate this problemTake an electric bus company as an example for EV energy network. Suppose an electric bus company in a city. All buses in the company are electric. Some buses have access to solar energy stations in rural area, and most of charge stations are placed in the city. Electric buses can transmit renewable power from energy sources in rural area to charge stations in the city.

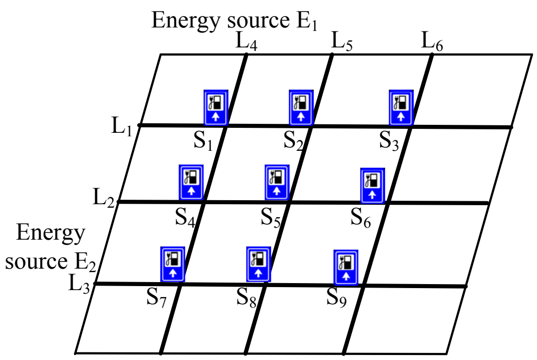

Fig. 1. Schematic diagram of bus lines

To simply illustrate the scenario, the schematic diagram of bus lines and bus stops, which includes 6 streets, 6 bus lines and 9 bus stops with charge stations, is shown in Fig.1. There are 6 bus lines: $L_1 : S_1 - S_2 - S_3, L_2 : S_4 - S_5 - S_6, L_3 : S_7 - S_8 - S_9, L_4 : S_1 - S_4 - S_7, L_5 : S_2 - S_5 - S_8, L_6 : S_3 - S_6 - S_9$. E_1 and E_2 are two renewable energy sources, which are in terminuses of bus line L_3 and L_4 . Charge stations may be set up in bus stops where two bus lines intersect. These charge stations get power energy from two energy sources. Energy may be transmitted from energy sources to charge stations by electric buses in bus lines. For example, charge stations S_7, S_8 and S_9 can get energy from E_2 through bus line L_3.

Charge stations in the EV energy network is different from charge stations for EVs. Charge stations for EVs get energy from the power grid and charge it to EVs immediately, as no energy storage is provided in them. The charge stations in the EV energy network are equipped with an energy storage unit, which can receive energy from EV and store energy in the energy storage unit. They can also charge EVs by their energy storage. In other words, the charge stations in the EV energy network can receive energy from one EV, store and then forward it to another EV. Their functions are similar to routers in the communication network. Charge stations in the EV energy network are called as energy routers. The router in the communication network only forwards packets. Energy routers, however, do not only forward energy but also charge EVs. At this point, energy routers are more similar to nodes in mobile ad hoc network, which are both routers and terminal users.

An energy router is an EV charge station with batteries. It has the function of charging power from EVs and discharging power to EVs. EV charge stations can store energy and forward energy like routers in the communication network. For example, energy router S_1 can accept energy from E_1 and forward it to S_2 . There is one energy router in every intersection in Fig.1.

The energy route metric is a number indicating the time of power charge and discharge in one energy route. Define one time of charge-discharge as metric one. The metric of the energy route $S_1 - S_2$ is one, for power energy is charged from S_1 to an EV and discharged from the EV to S_2. The metric of the the energy route $S_1 - S_5$ is 2, for two times of charge-discharge are needed. The first process is that power energy is charged from S_1 to an EV and discharged from the EV to S_2. The second process is that power energy is charged from S_2 to another EV and discharged from the EV to S_5.

Note that there is a difference between the energy route metric and the net metric. There is one bus line $L_1 : S_1 - S_2 - S_3$ in Fig.1. The metric of the energy route $S_1 - S_3$ is 1, for there is only one time of charge-discharge in the route, namely energy is charged from S_1 to an EV and then discharged from the EV to S_3. If there is only one bus line in the energy route, all of the metrics in the energy route equal one, for there is only one time of charge-discharge between any two energy routers in the energy route. A function M(r) can be used to calculate the energy route metric. For example, M(r_{S_1,S_4}) denotes the metric of the energy route $S_1 - S_3$. M(r_{S_1,S_3})=1. M(r_{S_1,S_5}) denotes the metric of the energy route $S_1 - S_5$ and M(r_{S_1,S_5})=2.

There is energy loss every time a charge-discharge process is completed. To reduce energy loss, charge-discharge times for transmission from renewable energy sources to charge stations should be minimized. In other words, the total number of energy route metric for all energy routes should be minimized. As the energy route metric is different from the net metric, the classical shortest route algorithms like Dijkstra's algorithm can not be directly used to find the shortest route [5].

IV. Problem Solution

To solve the problem that the energy route metric is different from the net metric in the above section, a hypergraph model is introduced to analyze the transform transportation network graph. A hypergraph G can be defined as a pair (V, E), where V is a set of vertices, and E is a set of edges between the vertices. A hypergraph is different from a graph in that each edge is a set of vertices. In the graph, each edge only has two vertices. Fig.2 is a hypergraph including 7 vertices and 3 edges. Edge E_1 includes V_1, V_2, V_3 and V_4. Edge E_2 includes V_4, V_5 and V_6. Edge E_3 includes V_6 and V_7.

There are any number of bus stops in every bus line in the bus transportation network. Similarly, there are any number of vertices in every edge of the hypergraph. Therefore, the hypergraph is suitable to be used to analyze the bus network.

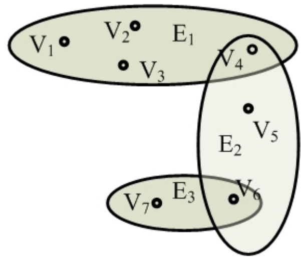

Fig. 2. An example of hypergraph

The hypergraph Fig.3 is transformed from bus network in Fig.1. There are 11 vertices including 9 charge stations and 2 energy sources. There are 6 edges including $L_1 = \{S_1, S_2, S_3\}, L_2 = \{S_4, S_5, S_6\}, L_3 = \{E_2, S_7, S_8, S_9\}, L_4 = \{E_1, S_1, S_4, S_7\}, L_5 = \{S_2, S_5, S_8\}, L_6 = \{S_3, S_6, S_9\}$. Since all of charge stations in one bus line is in the same edge, the energy route metric between any pair among them is one. For example in bus line3, M(r_{E_2,S_7})=M(r_{E_2,S_8})=M(r_{E_2,S_9})=1.

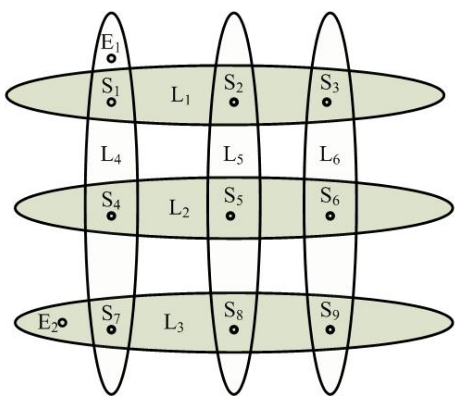

Fig. 3. The hypergraph of bus line

After the bus network graph is transformed into a hypergraph, every bus line is changed into one edge. This satisfies that all charge stations in the same bus line have the same metric, which solves the problem that the energy route metric is different from net metric in the above section. Then the classical shortest route algorithms like Dijkstra's algorithm can be used to find the shortest route.

In Section II shows that the key problem is how to schedule and transmit energy in the EV energy network with minimal cost. There are two points in this problem. One is the energy schedule for energy generations and energy demands. The other one is how to select the route to transmit energy from energy sources to energy users. In other words, there are several renewable energy sources which can generate different power capacity in the EV energy network. There are also many energy users like charge stations which have different energy consumption request in the EV energy network. How to minimize the total cost to transmit energy from energy sources to energy users is equivalent to the Vehicle Routing Problem, which is a classical NP-hard problem [6].

Algorithm 1: Energy Schedule Algorithm

1 $D \leftarrow$ all charge stations;
2 $S \leftarrow$ all renewable energy sources;
3 R_i denotes charge station i's energy request;
4 E_i denotes energy source i's energy supply;
5 construct hypergraph G by transportation and bus line;
6 $hop = 1$;
7 $cost = 0$;
8 **while** $D \neq \emptyset$ *and* $S \neq \emptyset$ **do**
9   **for** $\forall s_i \in S$ **do**
10   **for** $\forall d_j \in D$ **do**
11   Find the shortest route $P_{i,j}$ from s_i to d_j in hypergraph G ;
12   **if** *M(*P_{s_i,d_j}*)=hop* **then**
13                 $E_{d_j} = E_{d_j} - R_{s_i}$;
14   cost=cost+R_{s_i}×hop;
15                 $S = S \setminus \{s_i\}$;
16   **if** E_{d_j}*=0* **then**
17                 $D = D \setminus \{d_j\}$;
18   hop=hop+1;
19 Return cost

In this section, a greedy algorithm is presented to solve the problem. The main idea of the algorithm is as follows. First, select each one energy source and find those charge stations which are one hop energy route away from the energy source. Distribute energy from the energy source to these charge stations. Then, select each another energy source and find those charge stations which are one hop energy route away from the energy source. Distribute energy from the energy source to these charge stations. This step is repeated until any one hop energy route from energy source to charge stations can not be found. The function is from line9 to line17 in Algorithm 1. Thirdly, select those charge stations which are two hops energy route away from energy sources and distribute energy to those charge stations which do not get energy from energy sources. This step is repeated until all energy in each energy source is run out. The algorithm is presented in Algorithm 1.

The algorithm is illustrated using the example in Fig.1. First, the algorithm selects those charge stations which are one hop away from energy sources. Charge stations S_1, S_4, S_7 are one hop away from energy source E_1. Charge stations S_7, S_8, S_9 are one hop away from energy source E_2. Assign energy of E_1 to charge station S_1, S_4, S_7 and energy of E_2 to charge station S_8, S_9. S_7 has gotten energy from E_1 and need not get energy from E_2 again. Then, the algorithm selects those charge stations which are two hops away from energy sources. They are S_2, S_3, S_5 and S_6. S_2 and S_3 can get energy transferred from S_1 by energy route $E_1 - S_1 - S_2$ and $E_1 - S_1 - S_3$. S_5 and S_6 can get energy transferred from S_4 by energy route $E_1 - S_4 - S_5$ and $E_1 - S_4 - S_6$. These energy routes are two hops from energy sources.

V. Simulation and Analysis

A. Experiment Setup

To evaluate the performance of the algorithm, two kinds of bus system are adopted. One is the bus map of Manhattan in New York [7]. There are 37 bus lines and about 400 bus stops in Manhattan. Select bus stops which are in the intersecting point between two or more bus lines as charge stations. After pre-processing bus map data, 159 bus stops are obtained. The other one is the bus map of the Pioneer Valley Transit Authority(PVTA) [8]. The Pioneer Valley Transit Authority is the largest regional transit authority in Massachusetts with 174 buses, 144 vans and 24 participating member communities to provide public transportation within the Pioneer Valley region. There are 34 bus lines and about 200 bus stops in PVTA. After pre-processing bus map data, 116 bus stops are obtained.

There are similar number of bus lines and bus stops for these two bus system, however, there are different features in two bus maps. The bus map of Manhattan is city public transportation and bus lines are quite dense like meshwork, while the bus map of PVTA is rural public transportation and bus lines are sparse.

The number of total hops, which is the sum of all route hops from energy source to charge stations, is calculated to test the algorithm. This metric represents the energy loss for transmission from energy source to charge stations in the EV energy network. The less is the number of total hops, the less is the energy loss in the transmission process. The number of route hops on each route from renewable energy node to charge station is calculated. The total route metric is the sum of route hops in all routes.

B. Experiment Results

In the simulation, the number of renewable energy sources varies from 1 to 10. For each case, place the renewable energy sources on the bus map randomly using independent random seeds to obtain the results. The process is repeated for 100 times to obtain averages. The proposed algorithm is implemented in Matlab R2010b. Compare the performance with the random algorithm.

Random Algorithm: For each energy source, selects a sequence of charge stations arbitrarily. Then find the shortest path from the energy source to these charge stations, and calculate the sum of route hops in all routes.

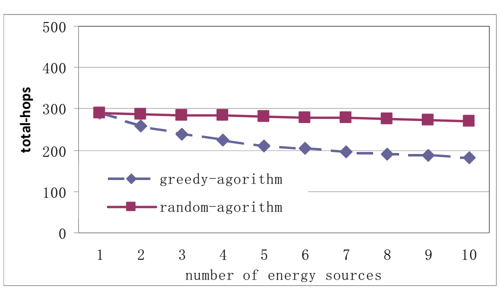

Fig. 4. Total hops under different numbers of energy sources in Manhattan

Fig. 4 shows total route hops from energy sources to charge stations in Manhattan with different numbers of energy sources. It can be observed that sum of total hops decreases with the increasing number of energy sources. It is because charge stations can find a shorter route from energy sources when the number of energy sources is increased. When more than one energy sources exist in the network, the results for two algorithms are the same, which is because charge stations are the same and only one energy source exists. The shortest routes from the energy source to all charge stations are also the same. Therefore, the total hops for these routes in two algorithms are equal.

When the number of energy sources is two or more, a greedy algorithm can be adopted to select those charge stations which are most close to energy sources, while the random algorithm only arbitrarily selects charge stations. Therefore, the sum of total hops for all energy routes in the greedy algorithm are less than that in random algorithm. With the increase of the number of energy sources, the greedy algorithm acquires better performance than the random algorithm. When the number of energy sources is ten, the sum of hops in the greedy algorithm is 182, while the random algorithm shows a sum of 270. The greedy algorithm shows a 32% decrease of total hops.

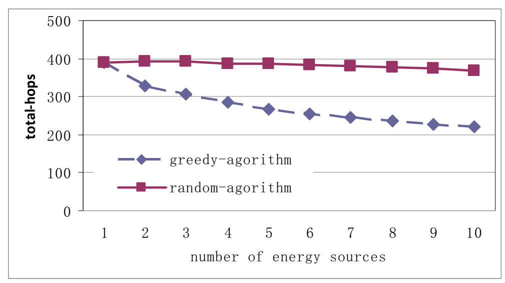

Fig. 5. Total hops under different numbers of energy sources in PVTA

Fig. 5 shows total route hops from energy sources to charge stations in PVTA while the number of energy sources varies. The simulation is similar to that in Manhattan. The total hops of the greedy algorithm are less than that of the random algorithm when there are more than one energy sources. The greedy algorithm obtains better performance with the increase of the number of energy sources. When the number of energy sources is ten, the sum of hops in the greedy algorithm is 222, while the random algorithm gets 368. The greedy algorithm decreases the sum of total hops by 40%.

Compare the result of two simulations in Manhattan and PVTA. The total hops of energy routes in PVTA are more than that in Manhattan. The greedy algorithm shows better performance in PVTA than that in Manhattan. The main reason is that there are different features in two bus maps. The bus map of PVTA looks like a star network. The top of the network is sparse. Most of bus lines are interconnected with other bus lines through one or two bus stops. It is difficult to find short energy routes from energy sources to charge stations. The bus map of Manhattan is much more like a mesh network. Most of streets are either from west to east or from north to south, and the top of network is dense, which all make it easier to find short energy routes from energy sources to charge stations.

VI. Discussion

In this section, the EV energy network is compared with the communication network and the power grid. Some potential problems of the EV energy network are discussed.

A. Comparison with the Communication Network

In EV energy network, EVs transfer energy from renewable energy (solar or wind) plants to users that need energy (e.g., charge stations and houses). Fig. 6 shows a schematic diagram of an EV energy network which is similar to the communication network. In the EV energy network, charge stations are treated as energy routers which can receive and forward energy. EVs in bus lines can transmit energy just like communication links in the communication network. EVs and charge stations compose an energy transmission and distribution network called as the EV energy network.

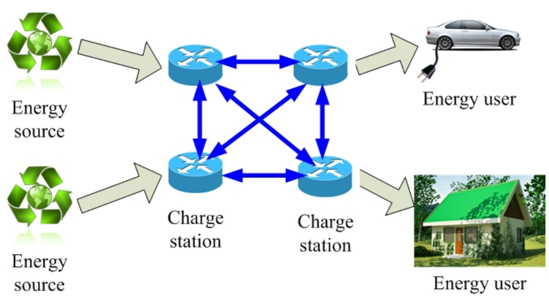

Fig. 6. Schematic diagram of an EV energy network

The EV energy network is similar to the communication network, in which charge stations are regarded as routers, EVs are regarded as link and energy is regarded as data packet. Energy can be transmitted by EVs from one charge station to another, just as packets are forwarded from one router to another.

Whereas there are some differences between the EV energy network and the communication network. First, packets transmitted in the communication network are all different from each other. For example, the packet which is sent to node A can only be received by node A. Energy in the EV energy network is the same. Energy users can receive and use any energy from any energy source. Moreover, the packet can not be changed when it is forwarded in the communication network. If some bytes are changed in the packet, the packet must be dropped and a new one will be resent by source node. When energy is transmitted in the EV energy network, part of energy will be lost because of the energy loss in charge-discharge process.

Furthermore, the speed of packet transmissions in the communication network is extremely fast, which can be compared with the speed of light. By contrast, the speed of energy transmissions in EV energy network is much slower. It may cost one hour or more to transmit energy from one energy source to users by EVs. In addition, packets can be bidirectionally transmitted in the communication network, while energy is only transmitted from sources to users. The above features are summarized in Table I.

TABLE I
Contrast between EV energy network and communication network

Name	EV energy network	communication network
Switching equipment	charge station	router
Transmission equipment	electric vechile	data link
Transmission object	energy	data
Transmission loss	energy loss	packet drop
Transmission delay	one hour or more	second
Transmission direction	one way	two way

B. Comparison with the Power Grid

The EV energy network can also be compared with the power grid because both of them transmit power energy form power plants to users. However, there is a difference between them because the transmit tools of the EV energy network are EVs, while that of the grid are power lines. The speed of energy transmissions in power line is very quick, while it may cost one hour or more to transmit energy in the EV energy network. The object of the power grid is regarded as a trunk to support all energy users. The object of the EV energy network is regarded as branches that help to transmit energy from renewable energy source to charge stations or other users. A detailed comparison is shown in Table II .

TABLE II
Contrast between EV energy network and power grid

Name	EV energy network	power grid
Transmission object	energy	energy
Transmission equipment	electric vechile	power line
Transmission loss	10%	30%
Transmission delay	one hour or more	second
Function	trunk	supplementary

We compare transmission efficiency between the EV energy network and the power grid from renewable energy sources to charge stations. The energy transmission process in the EV energy network is composed of three steps. First, charge EVs using DC power, which uses DC/DC converter with efficiency of 95% [9]. Secondly, energy is transmitted by EVs from energy sources to charge stations. It almost does not cost anything to transmit energy by electric buses, for electric buses travel on fixed bus lines many times in every day, which provide free ride to all the energy they carried. The main loss is through battery discharge (0.13% loss per day [10]). Thirdly, charge batteries in charge stations from EVs. The energy lose is around 5% [9]. In summary, the total power loss of the entire process is about 10%.

The energy transmission in power grid also consists of three steps. First, convert DC power generated by the solar panels into grid-ready AC power. It use DC/AC inverter (The SW 3000 inverter/charger of Xantrex Technology Inc.) [11], whose efficiency is 90%. Secondly, energy is transmitted by power lines, which incurs a loses of about 7.5% [12]. Thirdly, convert AC power to DC power to charge batteries in charge stations with an efficiency of 85% (Intelligent VS Power in Emerson

Network Power Inc.) [13]. The total power loss of the entire process is about 30%.

C. Feasibility

The rapid development and major accomplishments in the battery technique have resulted in the significant development of EVs [14]. New electric vehicles should be equipped with advanced batteries that will be able to withstand at least 10000 rapid charges, and be fully charged in less than 10 mins without any issues or performance degradation [15]. Researchers in MIT find a kind of battery materials can achieve full battery discharge in 10-20s [16]. Another kind of electric buses, called as super-capacitor bus, was put into use in Shanghai World Expo in China in 2010 [17]. The time of fully charging for super-capacitor buses is between 30s and 180s [18].

Winston Global Energy Holdings Limited has produced electric bus EV-2008 [19]. The total energy capacity of the battery pack in EV-2008 is more than 350Kwh. The battery pack is composed of 156 units WB-LYP700AHA [19], each of which weights about 21Kg. The weight of the battery pack in electric bus EV-2008 is 3276Kg. The net weight of EV-2008 is 11000Kg including the battery pack. The cost of per 100Km range is about 70Kwh. In other words, if the distance of a round-trip for one bus line is less than 100 Km, EV-2008 may transmit about 250Kwh energy in one round-trip, which means that batteries equipped in EV-2008 is enough to transmit energy without extra batteries.

If the electric bus EV-2008 need take an extra battery to transmit energy, how much it will cost in transmission? By technical introduction of EV-2008, the net weight is 11000Kg and the weight of a battery pack is 3276Kg. The cost of per 100Km range is about 70Kwh. We can get about 21Kwh in 70Kwh for battery pack transportation. Therefore, it will cost about 21 Kwh per 100 Km to transmit 350 Kwh by an extra battery pack. It costs only 6% energy to transmit 350 Kwh/per 100Km. The cost for energy transmission is very little.

D. Other Problems

Like the communication network, there is congestion in the EV energy network. For example, one energy route will be blocked when one street in the energy route is jammed with cars. Traffic jam may be the main reason to congestion in energy routes. In addition, when the batteries in charge station is full, no more energy can be received by charge stations, which also cause congestion in energy routers. Multi-path energy routes from energy sources to users may be a solution to this problem.

The EV energy network has some advantages. First, a lot of renewable energy (solar energy and wind energy) does need connect and transmit by electrical grid, if their generating energy can be transmitted by the EV energy network. It reduce the impact from the unstable renewable power on electrical grid. Secondly, the EV energy network can transmit energy to energy users partly instead of electrical grid. This will reduce some investment for power line. Thirdly, energy transmission by EVs is more efficient than by electrical grid for it need not DC/AC inverter and AC/DC converter. Energy transmission by electrical grid wastes more energy in two conversion processes.

Of course, there are also some disadvantages in the EV energy network. Energy transmission by the EV energy network from renewable source to user costs more time than that by the power grid. Charge stations and users need add energy storage units like batteries. Electric Vehicles carrying redundant power from renewable energy sources may need extra time to offload energy to charge station and users in demand.

VII. Conclusions

In this paper, the energy schedule and allocation problem in the EV energy network. A hypergraph model is used to analyze the transportation map, and then a greedy algorithm is adopted to schedule energy from energy sources to users. The bus map data of Manhattan in New York city and the Pioneer Valley region in Massachusetts(PVTA) is used to test the algorithm. Simulations show that the algorithm is efficient.

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