Short Paper

On Optimality Criteria for Reverse Charging of Electric Vehicles

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Abstract—Ever increasing expectations regarding the penetration level of electric vehicles (EVs) are driving several areas of research related to EV charging. One topic of interest treats EVs not only as controllable loads but also as storage systems, which can be used to mitigate the load on the grid during peak times by offering power. This is known as vehicle to grid (V2G). Since returning energy to the grid affects mobility patterns, V2G has an associated environmental cost. In this paper, to investigate this issue, we formulate the problem of returning electrical load to the grid as an optimization whose goal is to return the desired energy in a fashion that minimizes the cost on the environment. We show that this optimization is highly complex, and in some circumstances, the cost of V2G can be prohibitive.

Index Terms—Electric vehicles, optimization methods, smart grids.

Nomenclature

The following terms are used throughout the paper:

PHEV Plug-in hybrid electric vehicle.
BEV Fully battery powered electric vehicle.
plant Power plant.
i Index (denotes a PHEV, a BEV, or a plant).
E_i Energy taken from i to supply the grid.
p Pollution coefficient due to vehicle utilization.
μ Pollution coefficient that prevents battery life reduction.
ν Pollution coefficient due to recharging operations of the vehicle.
r_d Desired driving distance.
r_a Available driving distance in full electric mode.
d Acceptable walking distance.
k Adjustment factor for driver behavior, route selection, weather forecast, extra individual power consumption.
l Adjustment factor for energy conversion losses.
Ψ Stored energy in the battery of the vehicle.
ΔE Missing energy until battery is fully charged, i.e., the total battery capacity is $\Psi + \Delta E$.
$\bar{E}$ Maximum energy deliverable by a power plant.
E_{req} Energy required by the grid.

I. Introduction

Awareness concerning greenhouse gases and air pollution in cities has increased in recent years, and the shift to more environmentally friendly transportation systems is now a worldwide goal [1], [2]. Plug-in hybrids (PHEVs) and BEVs are considered as "green" alternatives to the combustion engine, and the deployment of such vehicles is now widely encouraged [3]. This interest is driving several active areas of research, including battery design, fast charging, grid-vehicle charge balancing, and distributed charging of fleets of electric vehicles. In addition to providing an alternative to fossil fuels, the main advantage of PHEVs is that they allow us to control where and when pollutants are released. For example, energy in battery form, irrespective of how it is generated, is delivered in a clean form within the city. Another purported advantage is that, due to the projected high penetration levels of such vehicles [4]–[7], they can be used to store energy when the grid produces excess energy and can be used to deliver this energy back to the grid in times of need. This concept is usually referred to as vehicle to grid (V2G) and is considered as a point of high potential for implementing peak shaving and valley filling policies.

The recent literature contains many examples of research work studying the V2G concept [8]–[10]. Issues considered include the ability of V2G to balance the demands of the grid with available supply, the cost returns of V2G operations, and the integration of renewable energy into the V2G concept. However, less attention has been paid to some of the other consequences of drawing power from a fleet of electric vehicles (EVs). In particular, given a certain demand for energy from the grid and an oversupply of available power from a fleet of EVs, the manner in which energy is drawn from the vehicle fleet may have a profound impact on the environment, as well as on individual commuters. For example, drawing power from an EV may affect the ability of the EV user to make certain trips. In cases where these trips are still possible, the user might still not be able to fully use the vehicle in electric mode. In both cases, an environmental cost is incurred as a result of the V2G concept.

In this paper, we investigate such issues. We do not argue the merits of V2G, or speculate whether it will emerge as a feature of road transportation. Rather, based on the assumption that V2G becomes a reality, we discuss key issues on intelligent transport systems that emerge when considering the management of the V2G concept. In particular, specific attention is paid to the various factors that have to be considered before drawing power from the EVs. These factors form a complex optimization problem, where three key points need to be addressed: 1) the effects on the environment; 2) the inconvenience for the vehicle owners; and 3) price. In this paper, we focus on the first of these issues, while some discussion regarding price issues can be found in [11]. In particular, we show here that poor management of the V2G concept may significantly mitigate the benefits of plug-in vehicles, namely, that of cleaner air in our cities. A key conclusion is that treating a fleet of EVs as a virtual storage system is not straightforward, due to the fact that the carbon footprint depends critically on the manner in which energy is drawn from the vehicles.

II. V2G AND THE ENVIRONMENT

We consider the following categories of willing participants in an energy exchange program with the electricity grid: BEVs; PHEVs; and power plants. We assume that there is a potential oversupply of energy to the grid. Thus, the allocation of energy from each participant to the grid is nonunique, and given this flexibility, the objective is then to compute the quantity of energy that each vehicle, and each power plant, has to supply to satisfy the requirements of the electricity grid while minimizing the impact on the environment. For each participant, we will construct a utility function that quantifies the impact on the environment in terms of emissions. The quantity of energy transferred to or from a participant is each utility function's independent variable. These utility functions are then used to formulate the optimization problem.

A. Utility Functions

We use utility functions to quantify the environmental cost of a participant supplying energy to the grid. We now list several factors that are important in deriving our utility functions. While we readily acknowledge that our list is not thoroughly exhaustive, we remark that our objective is to illustrate and emphasize the variety of hitherto ignored factors and the potential complexity of the optimization problem. Note that these utility functions can be easily adapted to include other factors of interest, as any given situation dictates, and can be modified to reflect more accurately the relationships between pollution and energy production.

Plug-in Hybrid Vehicles: The environmental footprint of a PHEV depends on several factors. First, if the desired driving distance is greater than the distance that the vehicle can drive in full electric mode, then the driver will switch to the vehicle's combustion engine when electric energy is depleted. This will have an impact on the environment through the use of carbon-based fuels. Therefore, taking electric energy from the vehicle has the effect of reducing its fully electric mode range, and potentially to produce pollutants. Note that the electric mode range cannot be computed trivially, as it depends itself upon several factors such as: the state of charge (SOC) of the battery pack; basic power consumption per kilometer; individual driving behavior; and usage of other electrical appliances (for example, heating, air conditioning, entertainment systems, headlights, or GPS) [13], [14]. The driven route also has a strong influence on the available full electric range, as power consumption varies according to the driving speed, the length of the journey, and the topology of the terrain. For instance, [12] shows how driving range can be maximized by thoughtful route selection. One more subtle factor that should be considered is related to losses caused by energy transfers. For example, continuous charging/discharging could reduce energy efficiency significantly.

Once the vehicle switches to the internal combustion engine, then the car produces air pollution, i.e., particulate matter, CO, and other carbon-related pollutants, as well as conventional greenhouse gases while driving. This production is dependent on the type of the car and the average speed of the vehicle. An important effect arises in some situations due to route choices that may depend on the availability of electric power. For example, in some German cities, environmental zones ("Umweltzonen") were introduced in 2008 [15]. The idea is that cars producing too much particulate matter and other pollutants should not be allowed to enter particular city zones. By taking electric energy from the vehicle, such restrictions could decrease the mobility of the owner and give rise to different and longer journeys with an associated increase in aggregate pollution production.

When driving in full electric mode, we assume that PHEVs do not exhaust any pollutants. On the other hand, the charging procedure does cause pollution due to battery degradation and pollution generated in producing the supplied charge.

Given such considerations, we now construct a sample utility function describing emissions due to energy transfer to, or from, a plug-in hybrid as follows. Let r_a (i.e., available driving range in full electric mode) be a piecewise linear function of the injected energy E_{PHEV}, i.e.,

$$r_a(E_{\mathrm{PHEV}}) = k(\Psi_{\mathrm{PHEV}} - lE_{\mathrm{PHEV}})$$

where $l > 1$ if $E_{\mathrm{PHEV}} \geq 0$, and $l < 1$ otherwise (according to the Nomenclature. Then, we consider a simple piecewise-linear convex utility function

$$f_{\mathrm{PHEV}}(E_{\mathrm{PHEV}}) = p\left(r_d - k(\Psi_{\mathrm{PHEV}} - lE_{\mathrm{PHEV}})\right) \\ + \mu + \nu(\Delta E_{\mathrm{PHEV}} + lE_{\mathrm{PHEV}}) \quad (1)$$

where the meanings of the parameters can be found in the Nomenclature. Fig. 1 illustrates some typical shapes of (1). The parameter p can be used to model either the air pollution, the CO_2 emissions, or a weighted combination of both as desired. We assume that $p > 0$ if $r_d > r_a$, and $p = 0$ otherwise, to reflect a PHEV's requirement to burn combustible fuel if the driver's desired driving distance is greater than the vehicle's available battery driving range. We use a pollution factor μ to avoid involving vehicles with a low SOC, i.e., *critical SOC*, in the V2G concept. In particular, we let $\mu = 0$ when the stored energy in the battery is above a certain level, whereas it increases when the battery discharges below that level to mitigate the effects of continuous charging/discharging on the battery lifetime. The last part of the utility function (1) accounts for the environmental effects of the usual charging (G2V) procedure. Therefore, we assume that ν is the average emission per kilowatthour of charging and that this is related to the air pollutant of interest. We also assume that the vehicle requires ΔE_{PHEV} units of energy to charge, plus the energy given to the grid as required. Note that ν depends on the position of the power plant relative to the vehicle (so that pollution in urban and rural regions may be treated differently, for example), and on the charging time (i.e., on-peak and off-peak hours).

Full EVs: BEVs are characterized by many of the factors that have been introduced in the previous section. For example, the expected demanded range has a direct influence on the environmental cost of taking power from a particular vehicle. Again, the available range depends on the stored energy in the battery, the nominal power consumption per kilometer, the chosen route, the weather conditions, and the usage of other electric appliances. In contrast to the previous discussion, the consequences of taking energy from the BEV owner might lead to behavioral change, as the owner can potentially remain without enough energy to complete a planned or desired journey. As a consequence, alternative transportation modes can be used, with an obvious inconvenience to the owner, and give rise to new sources of pollution. While the consequences and the effects on the environment are difficult to predict in advance, some issues are now briefly illustrated.

Recharging: The owner may recharge the EV either on the journey or keep it connected at home for an additional period. The emissions due to the extra charging period depend only on the generation side.

Second car: The owner may have a second car available as a replacement. In this situation the additional pollution depends on whether it is a BEV, a PHEV, or a conventional combustion engine car. Then, emissions depend on the nominal emissions per kilometer for the combustion engine case or on the SOC for an EV.

Public transport: Whether public transport can be a valid alternative to BEVs depends on the local availability of public transportation,

Fig. 1. Utility functions of the PHEVs, depicted with thick lines, are obtained by combining single contributions, depicted with dashed lines. The single contributions mainly depend on the current SOC of the battery, and on how much it is expected that the battery will be used in the next trip. This figure illustrates three examples of utility functions for different working conditions.
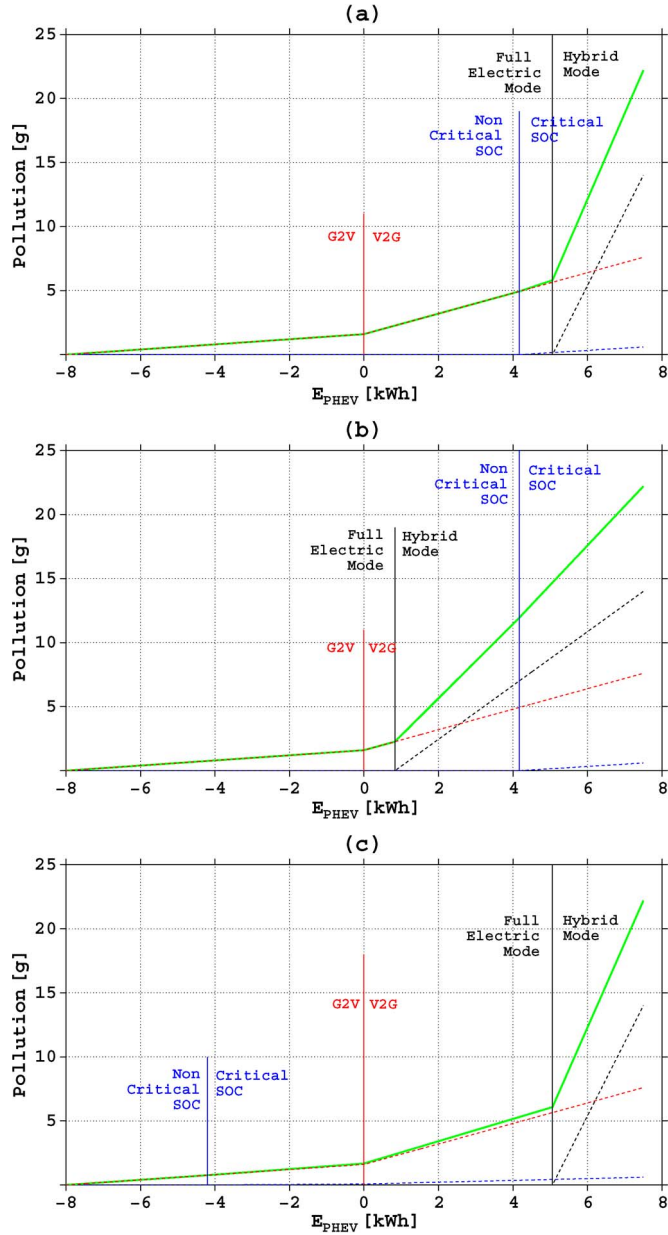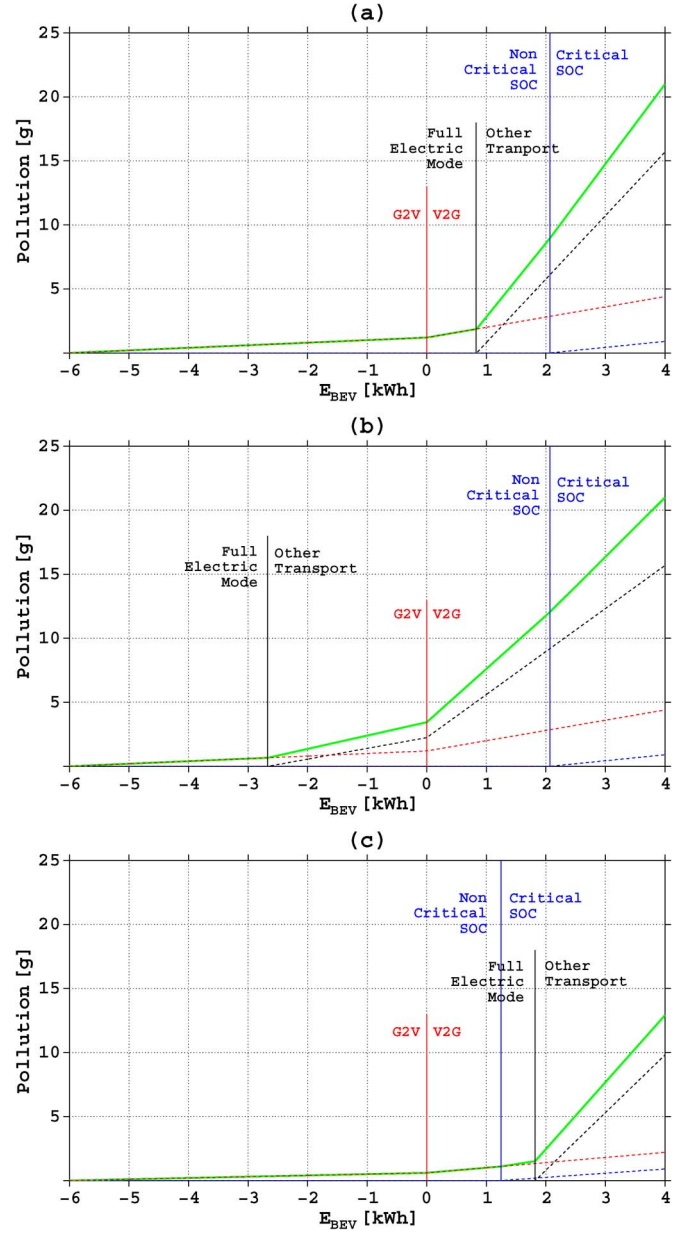

Fig. 2. Utility functions of the BEVs, depicted with thick lines, are obtained by combining single contributions, depicted with dashed lines. The single contributions mainly depend on the current SOC of the battery, and on how much it is expected that the battery will be used in the next trip. This figure illustrates three examples of utility functions for different working conditions.

costs, efficiency, and expected pollution. For example, a highly developed and environmentally friendly system could increase the environmental benefits, while keeping the inconvenience for the owner small.

Other measures: If the owner has none of the previous possibilities for alternative transportation, then the inconvenience for the owner is extremely high. To reflect this fact, the corresponding utility function is designed to incorporate a high penalty costwise for energy depletion.

We now construct a utility function adopting factors similar to those for the PHEV case. In particular, let us assume again that $r_a(E_{\text{BEV}}) = k(\Psi_{\text{BEV}} - lE_{\text{BEV}})$, where $l > 1$ if $E_{\text{BEV}} \geq 0$, and $l < 1$ otherwise. Furthermore, it is assumed that the owner has only one alternative; hence, in the case that the remaining energy is not enough to complete any planned journeys, then the owner of the vehicle uses a mode of

alternative transportation. We assume that a distance d is the maximum walking distance that an EV user will walk; hence, if the missing range is smaller than d, then no pollution is caused. Otherwise, pollution is caused for each remaining kilometer. Factors μ and ν have the same meaning as before. Note that parameters p, μ, and ν can be also used to include the information of where the pollution is produced and to reflect the fact that the impact of pollution on people can be more severe in particular areas (i.e., close to hospital, kindergartens, etc.).

An example utility function for the pollution is then

$$f_{\text{BEV}}(E_{\text{BEV}}) = p(r_d - d - k(\Psi - lE_{\text{BEV}}))$$
$$+ \mu + \nu(\Delta E_{\text{BEV}} + lE_{\text{BEV}}) \quad (2)$$

where $p > 0$ if $E_{\text{BEV}} > (k\Psi_{\text{BEV}} - r_d + d/lk)$, and $p = 0$ otherwise. Some sample utility functions are depicted in Fig. 2.

Power Plants: Power plants enter the energy exchange program as in some situations that the electric grid might find it more convenient to request a power plant to increase its production, if possible, to provide the extra required energy than taking the same energy from EVs. Generators differ from vehicles, as power delivery is their main task. However, similar to the discussion concerning EVs, we also model here a utility function associated with power plants in terms of their environmental impact. For this purpose, we only consider power plants that are able to regulate their power output. Reserves for sudden failing of other generators, and short-time demand and power matching spinning reserves, are not considered. The utility function takes into account the air pollutants and emissions caused by a power plant, as a function of the produced energy, and the pollution caused by modulating the power output.

Waste: The generation of energy produces some amount of waste. The disposal of this waste has to be taken into account in our optimization (in terms of extra costs and negative environmental effects).

Raw materials: As most generators burn raw materials, the pollution, the effects on the environment, and the cost of their production and transportation have to also be taken into account.

Construction, maintenance, and **dismantlement of the power plant:** These also contribute an extra pollution cost.

Efficiency and **losses:** The efficiency with which the power plant is able to transform the energy from the raw material into electric energy is crucially related to the amount of pollution that will be produced. The more efficient this process is, the less raw material is used, and waste is produced per unit of generated power, and thus, the pollution resulting from the process is also reduced. Furthermore, the transmission and distribution of the power is accompanied by additional energy losses. Those transmission losses become particularly apparent when the distances are large. If the distribution distances are small, then the losses are smaller, and this, in turn, allows the power plant to decrease the power output and, hence, the air pollution generated.

Note that, although some of the factors (e.g., installment costs) do not depend on instantaneous power production, they are still among the major sources of CO_2 emissions and air pollutants associated with power generation, and for this reason, it is important to take them into account [16], [17].

We assume that the relationship between the energy delivered by the power plant and the resultant production of pollution is linear. While this relationship is an approximation of the true relationship [22], it is commonly used in the literature as it represents a good tradeoff between simplicity and accuracy; see, for instance, [17], [23], and [25]. Furthermore, we assume a loss factor of $l_{\text{plant}} > 1$ of the delivered energy to account for the energy conversion losses. This results in the utility function

$$f_{\text{plant}}(E_{\text{plant}}) = p_{\text{plant}} l_{\text{plant}} E_{\text{plant}} \tag{3}$$

where resource and waste are taken into account within the factor p.

Comment: We have introduced the utility functions to formulate various optimization problems. These utility functions were chosen to be relatively simple to illustrate basic concepts. Context-based criteria, such as driver's driving style, route choice, anticipated congestion and time of journey, and weather, have all been gathered within the parameter k in the utility formulation. In addition, the existence of a spinning reserve and the geospatial aspects of the grid have been completely ignored. We emphasize that the utility functions can be easily extended to further emphasize, or to include, other factors of interest that have been approximated or neglected for the sake of exposition.

TABLE I
PARAMETER VALUES FOR PARTICIPATING VEHICLES AND POWER PLANT

	BEV 1	BEV 2	PHEV 1	plant 1 ; 2
p [g/km]	0.4369	0.5509	0.3149	n/a
p [g/MJ]	n/a	n/a	n/a	0.573
μ [g]	0.05	0.05	0.05	n/a
ν [g/kWh]	0.35	0.15	0.5	n/a
r_d [km]	20	30	40	n/a
d [km]	0.4	0.3	n/a	n/a
k [km/kWh]	7	4.1	3.7	n/a
l $(E_i \geq 0)$	1.05	1.05	1.05	1.08
l $(E_i < 0)$	0.95	0.95	0.95	n/a
Ψ [kWh]	6	7	12	n/a
ΔE [kWh]	18	17	4.5	n/a
$\bar{E}$ [kWh]	n/a	n/a	n/a	50

B. Optimization Problem

The optimization problem of interest is now stated below and illustrated through some examples. The objective is to provide the required V2G energy in a region of interest. The problem is solved every time step (e.g., every half an hour). Much shorter time steps on the order of seconds can, however, be chosen if required. Our optimization problem formally is given as follows:

$$\min_{E_i} \sum f_i(E_i) \tag{4}$$

subject to the constraints

$$\sum E_i = E_{\text{req}} \tag{5}$$

$$-\Delta E_i \leq E_i \leq \Psi_i \quad (i \in \{\text{PHEV, BEV}\}) \tag{6}$$

$$0 \leq E_i \leq \bar{E}_i \quad (i \in \{\text{plant}\}). \tag{7}$$

Equation (4) states that we want to minimize the sum of pollutants produced. Equation (5) states that we wish to deliver a desired amount of energy to the grid. The rest of the equations are additional constraints due to the energy network and battery constraints. Note that the constraints (6) indicate that energy can be added to the vehicles rather than taken away if doing so benefits the environment, provided that enough energy can be drawn from the participating power plants to compensate the needs of the electricity grid. Furthermore, all of our utility functions $f_i(E_i)$ were chosen in the previous sections of this note to be convex, such that solutions to the optimization problem can be found.

In all of our following examples, we assume that three vehicles are willing to participate in the V2G energy exchange program and that the electricity grid requires 18 kWh (which is an arbitrarily chosen quantity, consistent with the small number of participating vehicles). The three vehicles participating are a PHEV and two BEVs, whose parameters are summarized in Table I under the entries BEV 1, BEV 2, and PHEV 1 for the two EVs and the plug-in hybrid, respectively. The pollution of interest is air quality [17] defined by aggregating the pollutants CO, NOx, SOx, and volatile organic compounds in a manner that reflects the health cost of each one, i.e., by weighting the sum using the coefficients 0.017, 1, 1.3, and 0.64, respectively, as per [17]. The choice of coefficients in [17] was based on data from the Australian Environment Protection Authority and from the Ontario Air Quality Index data. Note that other pollutants of interest, or CO_2

TABLE II
EQUAL CONTRIBUTION: ENERGY CONTRIBUTION
AND RESULTING ENVIRONMENTAL COST

	BEV 1	BEV 2	PHEV 1	Total
E_i [kWh]	6	6	6	18
f_i [g]	18.0389	18.3184	11.3702	47.7274

TABLE III
POLLUTION MINIMIZATION: ENERGY CONTRIBUTION
AND RESULTING ENVIRONMENTAL COST

	BEV 1	BEV 2	PHEV 1	Total
E_i [kWh]	3.0476	3.0755	11.8768	18
f_i [g]	7.4408	10.8901	21.6826	40.0135

TABLE IV
POLLUTION MINIMIZATION INCLUDING POWER PLANTS: ENERGY
CONTRIBUTION AND RESULTING ENVIRONMENTAL COST

	BEV 1	BEV 2	PHEV 1	plant 1	Total
E_i [kWh]	3.0476	-0.2567	11.9556	3.2535	18
f_i [g]	7.4408	2.5134	21.8209	7.1906	38.9658

emissions, can be considered as well, by simply adapting parameters p, μ, and ν.

In the examples, we assume that the BEV owners will take alternative means of transportation if required. Therefore, each parameter p associated with a BEV is chosen to correspond to a pollution level that is somewhere between that of a PHEV and a conventional combustion engine car [17]. Their batteries and range abilities are those documented for a Nissan Leaf under different environmental conditions [14]. The SOC and d are chosen arbitrarily. The energy requirements and battery size of the PHEV correspond to those documented for a Chevrolet Volt [18]. The pollution factor p associated with the PHEV is chosen to replicate the air pollution level of a nominal PHEV [17]. Values for parameter ν are taken from [17], by considering a scenario where most of the power is generated from renewables while a small portion comes from gas power plants. The parameter μ is chosen arbitrarily to prevent the reduction of battery lifetime. Finally, we consider one gas power plant as a participant in the energy exchange program in some of our examples as an extra power station that can be fired up to draw energy from, in addition to the EVs (the gas power plant has its own corresponding pollution factor, again taken from [17]).

Example 1 (Naive Solution—Everybody Contributes Equal Amounts of Energy): In the first example, we assume that all vehicles equally contribute to the V2G operations. The resulting environmental costs are summarized in Table II. The total cost to the environment is 47.7274 g. Note that such naive solutions are usually considered in the context of V2G operations, i.e., either all available vehicles equally support V2G facilities, or perhaps do so based on a pricing model, or on the current level of their batteries [19].

Example 2 (Pollution Minimization): We now repeat the previous example within our optimization framework. As previously described, the objective is still to provide 18 kWh of energy, but in such a way as to minimize the environmental cost of the V2G operations. The corresponding optimization problem can be stated as

$$\min f_{\mathrm{PHEV1}} + \sum_{j=1}^{2} f_{\mathrm{BEV}j} \qquad (8)$$

$$\text{s.t. } E_{\mathrm{PHEV1}} + \sum_{j=1}^{2} E_{\mathrm{BEV}j} = E_{\mathrm{req}} \qquad (9)$$

where E_{req} is the required total energy (by the grid) for the next time period (i.e., 18 kWh), and $j = 1, 2$ specifies the vehicles BEV 1 and BEV 2. Additionally, the optimization variables are subject to the battery capacity constraints

$$-\Delta E_{\mathrm{BEV}j} \leq E_{\mathrm{BEV}j} \leq \Psi_{\mathrm{BEV}j}, \qquad j = 1, 2 \qquad (10)$$

$$-\Delta E_{\mathrm{PHEV1}} \leq E_{\mathrm{PHEV1}} \leq \Psi_{\mathrm{PHEV1}} \qquad (11)$$

which implies that vehicles can discharge (V2G) not more than their current energy stored in the battery and can be charged (G2V) without exceeding the battery capacity. The minimization problem can be easily and rapidly solved using standard convex optimization techniques (see, for instance, [20]). In our example, we found the optimal solution

using the classic general-purpose MATLAB function *fmincon* with the default trust-region-reflective algorithm. The pollution minimization approach, as shown in Table III, shows that the desired energy can be delivered while reducing the total pollution to 40.0135 g, which is a reduction of more than 15% with respect to the previous solution. This example shows that a careful choice of which (and how many) vehicles should participate in the V2G program can make a significant difference to the environment.

Example 3 (Pollution Minimization Including Power Plants): We now consider the effect of allowing the power management company to switch on the new generating capacity. As before, the sum of the individual utility functions, including the environmental costs caused by power plants, is our objective function to be minimized. The problem is how to draw energy for the next time-step of the different parties in a way that minimizes the impact on the environment. As in Example 2, the vehicles are also allowed to draw power if this helps to decrease the environmental cost. Thus, the optimization problem is

$$\min f_{\mathrm{PHEV1}} + \sum_{j=1}^{2} f_{\mathrm{BEV}j} + f_{\mathrm{plant1}} \qquad (12)$$

$$\text{s.t. } E_{\mathrm{PHEV1}} + \sum_{j=1}^{2} E_{\mathrm{BEV}j} + E_{\mathrm{plant1}} = E_{\mathrm{req}} \qquad (13)$$

where E_{req} is the required total energy for the next time period. Additionally, the optimization variables are bounded by

$$-\Delta E_{\mathrm{BEV}j} \leq E_{\mathrm{BEV}j} \leq \Psi_{\mathrm{BEV}j}, \qquad j = 1, 2 \qquad (14)$$

$$-\Delta E_{\mathrm{PHEV1}} \leq E_{\mathrm{PHEV1}} \leq \Psi_{\mathrm{PHEV1}} \qquad (15)$$

$$0 \leq E_{\mathrm{plant1}} \leq \bar{E}_{\mathrm{plant1}} \qquad (16)$$

where ΔE_i is the required energy until the battery is fully charged, and $\bar{E}_{\mathrm{plant1}}$ is the maximal energy that can be delivered from plant 1. As shown in Table IV, the optimal solution is to take energy from BEV 1, PHEV 1, and from the power plant, and to deliver some energy to BEV 2. The total pollution is 38.9658 g, which corresponds to a reduction of nearly 20% of the pollution caused in Example 1. Note that this example suggests that, in some cases, it might be preferable to generate new energy (from available power plants) than to take such energy from the plug-in fleet.

Example 4 (Utility Fairness): In a dynamic market situation where users sell energy back to the grid, the previous optimization results may be very unsatisfactory for individual users and cause much disruption to certain customer types. For example, a utility company would frequently drain energy from low polluting cars and green users,
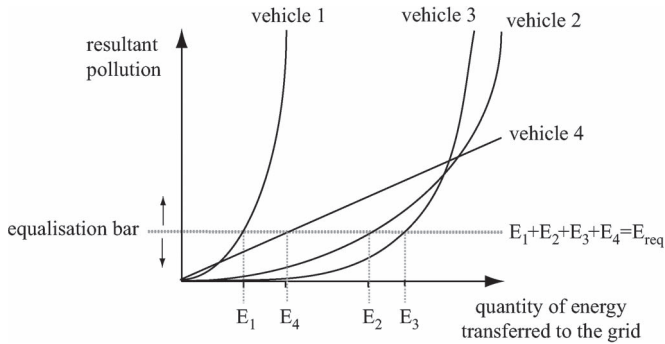
Fig. 3.   Utility fairness: the notion is to ensure that the cost to the environment caused by each of the participants in the energy exchange program is the same. The solid lines represent the utility functions of the participants; in this case, four arbitrary vehicles with convex utility functions. The equalization bar is dragged up and down the vertical axis until the sum of the energy drawn from each vehicle is equal to the energy required by the electricity grid.

resulting in those vehicle owners having to make alternative arrangements for unexpected trips. Under this scheme, the batteries of low polluting cars/green users also undergo more frequent charge cycles, degrading battery life more quickly. Meanwhile, higher polluting vehicles/users are not penalized at all. Of course, such users probably have a financial benefit. Nevertheless, one alternative method to achieve fairness in the network is to use the utility functions to dictate how much energy each user gives back to the network; this is known as utility fairness [21]. Fig. 3 illustrates this idea. Here, we ensure that the environmental cost to each user is the same. The previous minimization problem becomes now an equalization problem that can be solved either in a centralized manner or in a decentralized manner, for instance, using implicit consensus techniques [21].

Comment: The optimization problem illustrated so far allocates the required V2G energy among a set of vehicles, in order to minimize or equalize environmental pollution. However, in the context of reverse charging of EVs, there can be other objectives of interest as well. The minimization of the financial costs of the grid operators is one such example. Generally speaking, such costs can be assumed to be proportional to the inconvenience caused to the participants, i.e., EV owners and power plants are willing to receive an incentive for V2G operations that is proportional to their inconvenience. The new optimal solution can still be found within the same framework, by simply designing different appropriate utility functions.

III. Concluding Remarks

In this paper, we give a new perspective on the V2G concept. Given a certain level of demand from the grid and a fleet of EVs and other participants, there are many ways in which this energy can be drawn. Our key conclusion is that poor choices in this context may have severe environmental effects, thereby mitigating one of the principal benefits of plug-in vehicles, namely, that of cleaner air in our cities.

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