On Optimality Criteria for Reverse Charging of Electric Vehicles

Sonja Stüdli, Wynita Griggs, Emanuele Crisostomi and Robert Shorten

***Abstract*—Ever increasing expectations regarding the penetration level of electric vehicles (EV) 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 optimisation whose goal is to return the desired energy in a fashion that minimises the cost on the environment. We show that this optimisation is highly complex and in some circumstances the cost of V2G can be prohibitive.**

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 (PHEV) and fully battery powered electric vehicles (BEV) 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. As well as providing an alternative to fossil fuels, the main advantage of plug-in electric vehicles 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, little attention has been paid to some of the other consequences of drawing power from a fleet of EVs. In particular, given a certain demand for energy from the grid, and an oversupply of available power from a fleet of electric vehicles, 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 electric vehicle 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 short 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 ITS issues 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 optimisation problem, where three key points need to be addressed: (i) the effects on the environment; (ii) the inconvenience for the vehicle owners; and (iii) 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 electric vehicles 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. 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	an index (denotes a $PHEV$, BEV or $plant$)
E_i	energy taken from i to supply the grid
p	pollution coefficient due to vehicle utilisation

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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 behaviour, 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

III. V2G and the Environment

We consider the following categories of willing participants in an energy exchange programme 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 non-unique, 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 minimising 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 optimisation 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 emphasise the variety of hitherto ignored factors, and the potential complexity of the optimisation 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 relationships between pollution and the 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 can not be computed trivially as it depends itself upon several factors such as: the state of charge of the battery pack; basic power consumption per kilometre; individual driving behaviour; 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 driving speed, the length of the journey, and the topology of the terrain. For instance, [12] shows how driving range can be maximised 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, namely 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}:

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

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

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

where the meanings of the parameters can be found in the nomenclature in Section II. Figure 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 state of charge (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, while 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 kWh 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, off-peak hours).

Full Electric Vehicles

BEVs are characterised 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 kilometre, 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 behavioural 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 km for the combustion engine case or on the state of charge for an EV.

Public transport: Whether public transport can be a valid alternative to BEVs depends on the local availability of public transportation, 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 above 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 cost-wise for energy depletion.

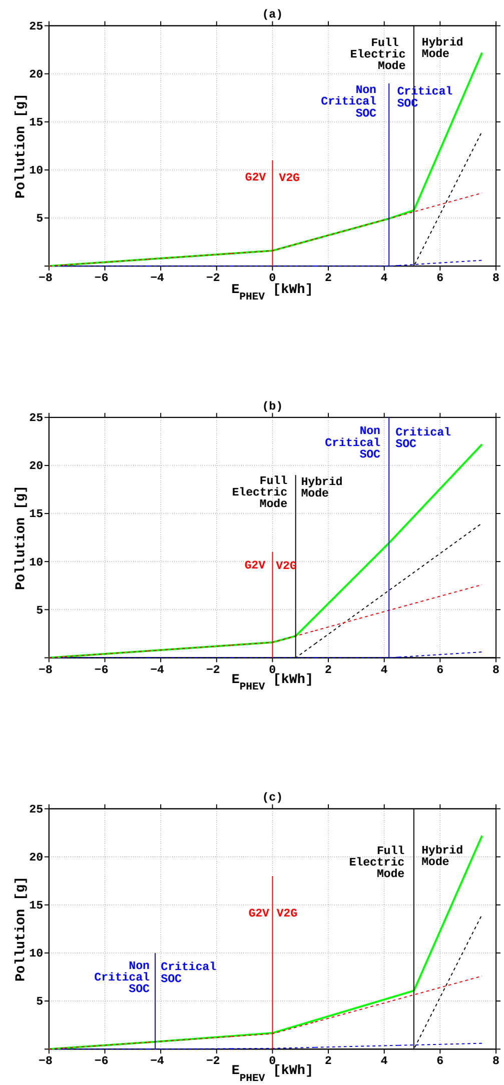

Fig. 1. The utility functions of the PHEVs, depicted with thick lines, are obtained by combining single contributions, depicted with dashed lines. The single contributions mainly depend on the current state of charge of the battery, and on how much it is expected that the battery will be used in the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

We now construct a utility function adopting factors similar to those for the PHEV case. In particular, let us assume again that $r_a(E_{BEV}) = k(\Psi_{BEV} - lE_{BEV})$, where $l > 1$ if $E_{BEV} \geq 0$ and $l < 1$ otherwise. Further, it is assumed that the owner has only one alternative, so 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, so if the missing range is smaller than d then no pollution is caused. Otherwise pollution is caused for each remaining km. Factors μ and ν have the same meaning as before. Note that the 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

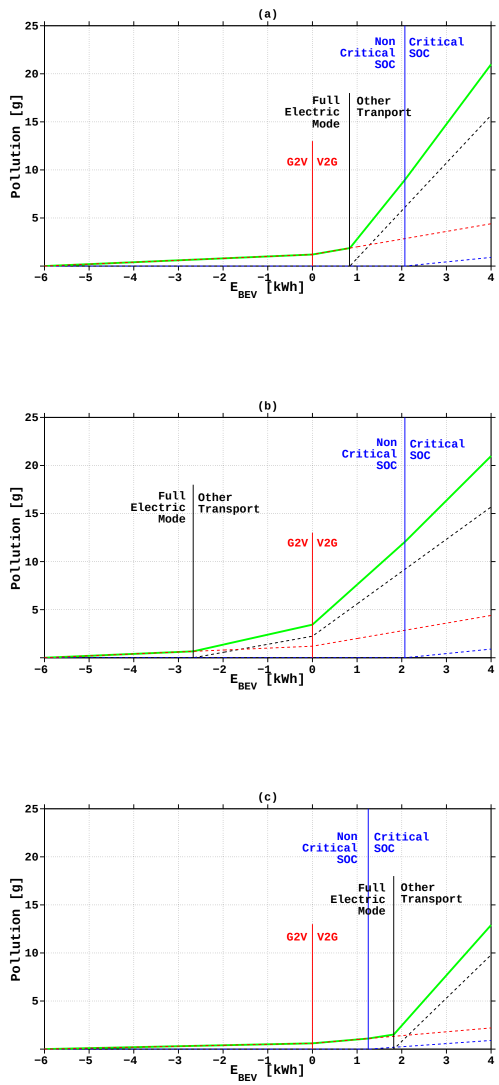

Fig. 2. The utility functions of the BEVs, depicted with thick lines, are obtained by combining single contributions, depicted with dashed lines. The single contributions mainly depend on the current state of charge of the battery, and on how much it is expected that the battery will be used in the next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

can be more severe in particular areas (i.e.: close to hospital, kindergartens, etc).

An example utility function for the pollution is then

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

where $p > 0$ if $E_{BEV} > \frac{k\Psi_{BEV} - r_d + d}{lk}$ and $p = 0$ otherwise. Some sample utility functions are depicted in Figure 2.

Power Plants

Power plants enter the energy exchange programme as in some situations 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 electric vehicles. Generators differ from vehicles as power delivery is their main task. However, similarly 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 optimisation (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 one [22], it is commonly used in the literature as it represents a good trade-off between simplicity and accuracy; see for instance [17], [23], [25]. Furthermore, we assume a loss factor of $l_{plant} > 1$ of the delivered energy to account for the energy conversion losses. This results in the utility function

$$f_{plant}(E_{plant}) = p_{plant} l_{plant} E_{plant}, \quad (3)$$

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

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

B. Optimisation Problem

The optimisation 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 of the order of seconds can however be chosen if required. Our optimisation problem formally is as follows:

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

subject to the constraints

$$\sum E_i = E_{req} \quad (5)$$

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

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

Equation (4) states that we want to minimise 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 optimisation problem can be found.

In all of our following examples, we assume that three vehicles are willing to participate in the V2G energy exchange programme, and that the electricity grid requires $18kWh$ (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 summarised in Table I under the entries BEV1, BEV2, and PHEV1 for the two electric vehicles and the plug-in hybrid, respectively. The pollution of interest is air quality [17] defined by aggregating the pollutants CO, NOx, SOx and VOCs in a manner that reflects the health cost of each one; namely, 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 emissions, can be considered as well, by simply adapting the 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 the 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 an energy exchange programme participant 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 summarised 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; namely 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 minimisation): We now repeat the above example within our optimisation framework. As previ-

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

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 MINIMISATION: 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

ously described, the objective is still to provide $18\ kWh$ of energy, but in such a way as to minimise the environmental cost of the V2G operations. The corresponding optimisation problem can be stated as:

$$\min f_{PHEV\,1} + \sum_{j=1}^{2} f_{BEV\,j} \tag{8}$$

$$\text{s.t. } E_{PHEV\,1} + \sum_{j=1}^{2} E_{BEV\,j} = E_{req} \tag{9}$$

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 $BEV1$ and $BEV2$. Additionally, the optimisation variables are subject to the battery capacity constraints:

$$-\Delta E_{BEV\,j} \leq E_{BEV\,j} \leq \Psi_{BEV\,j}, \quad j = 1, 2 \tag{10}$$
$$-\Delta E_{PHEV\,1} \leq E_{PHEV\,1} \leq \Psi_{PHEV\,1} \tag{11}$$

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 minimisation problem can be easily and rapidly solved using standard convex optimisation 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 minimisation approach, as can be seen from 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 programme can make a significant difference to the environment.

Example 3 (Pollution minimisation including power plants): We now consider the effect of allowing the power management company to switch on new generating capacity. As before, the sum of the individual utility functions, including the environmental costs caused by power plants, is our objective

TABLE IV
POLLUTION MINIMISATION 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

function to be minimised. The problem is how to draw energy for the next time-step of the different parties in a way that minimises 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. The optimisation problem thus is

$$\min f_{PHEV\,1} + \sum_{j=1}^{2} f_{BEV\,j} + f_{plant\,1} \tag{12}$$

$$\text{s.t. } E_{PHEV\,1} + \sum_{j=1}^{2} E_{BEV\,j} + E_{plant\,1} = E_{req} \tag{13}$$

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

$$-\Delta E_{BEV\,j} \leq E_{BEV\,j} \leq \Psi_{BEV\,j}, \quad j = 1, 2 \tag{14}$$
$$-\Delta E_{PHEV\,1} \leq E_{PHEV\,1} \leq \Psi_{PHEV\,1}, \tag{15}$$
$$0 \leq E_{plant\,1} \leq \bar{E}_{plant\,1}, \tag{16}$$

where ΔE_i is the required energy until the battery is fully charged and $\bar{E}_{plant\,1}$ is the maximal energy that can be delivered from plant 1. As can be seen from 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 $38.9658g$, 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 above optimisation 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, resulting in these 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 penalised 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]. Figure 3 illustrates this idea. Here we ensure that the environmental cost to each user is the same. The previous minimisation problem becomes now an equalisation problem that can be solved either in a centralised manner, or in a decentralised manner, for instance using implicit consensus techniques [21].

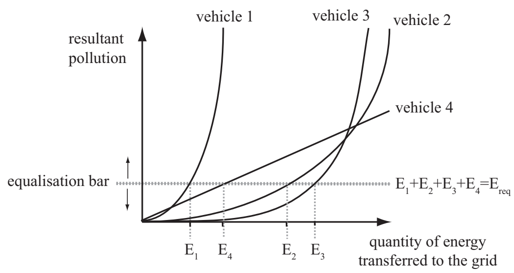

Fig. 3. Utility fairness: the notion is to ensure that the cost to the environment caused by each of the energy exchange programme participants is the same. The solid lines represent the utility functions of the participants; in this case, four arbitrary vehicles with convex utility functions. The equalisation bar is dragged up and down the vertical axis until the sum of the energy drawn from each vehicle equals the energy required by the electricity grid.

Comment: The optimisation problem illustrated so far allocates the required V2G energy among a set of vehicles in order to minimise or equalise environmental pollution. However, in the context of reverse charging of electric vehicles, there can be other objectives of interest as well. The minimisation 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.

IV. 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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