# Toward Mitigating Electric Vehicles Impact on Power System: A Planning Approach

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Abstract—With the rapid growth of electric vehicles, power systems would face serious difficulties to supply the excessive electricity demand in the near future. In this paper, a bilevel planning method is introduced to prevent the environmental and technical issues that the introduction of electric vehicles may cause for electricity grids. The idea of this method is to employ the differences between EV types and optimally distribute them within the power system. The planning objective, modeled by the upper-level problem, is to minimize the total CO<sub>2</sub>. This upper-level problem is constrained by a lower-level optimal power flow. The model is reduced to a single-level convex optimization problem using the duality theory. The importance of decreasing urban area emission is also considered in this model. The IEEE RTS 24 system, and real world vehicle specifications is used to demonstrate the capability of the proposed method. Results suggest that for low daily trip distances, the best option depends on the priority of urban area emission reduction. On the other hand, for higher distances, the plug-in types would lead to lower total emissions.

Keywords—Bilevel model, CO<sub>2</sub> emissions, Duality theroy, Planning, Electric Vehicle

## NOTATION

Indices and Sets

- *i*,*j* Index of system buses
- t Index of time slots
- *u* Index of generating units
- b Index of blocks of generating units heat rate
- *l* Index of transmission lines
- w Index of scenarios
- **B** Set of system buses
- T Set of time slots
- **G** Set of generation units
- $\mathbf{B}_{\mathbf{u}}$  Set of blocks of generating units heat rate of unit
- W Set of scenarios

Variables

- $x_{i,phev}$  Number of PHEVs in bus *i*
- $x_{i,hev}$  Number of HEVs in bus *i*
- $x_{i,pev}$  Number of PEVs in bus *i*
- Pg Total amount of power generation of units
- F Transmission line power
- $\delta$  Voltage angle of system buses

EVload Total load of EV charging at bus

### Constants and input data

d	Daily trip distance for all vehicles
$demand_{pev}$	Amount of electricity used by a PEV in one-day trips
<i>demand</i> <sub>phev</sub>	Amount of electricity used by a PHEV in one-day trips
AER	All-electric range of PHEVs
$bc_{pev}$	Battery capacity of PEVs
$bc_{phev}$	Battery capacity of PHEVs
$C_{pev}$	PEV charger's rated power
$C_{phev}$	PHEV charger's rated power
$T_{pev}$	Needed time to fully charge a PEV
$T_{phev}$	Needed time to fully charge a PHEV
$L_{pev}$	Load of charging a PEV in every time slot
Lphev	Load of charging a PHEV in every time slot
$e_{phev}$	Total CO <sub>2</sub> emitted in one day from a PHEV
$e_{hev}$	Total CO <sub>2</sub> emitted in one day from an HEV
$CPK_{hev}$	CO <sub>2</sub> emission rate of HEVs
$CPK_{phev}$	CO <sub>2</sub> emission rate of PHEVs while using electricity
В	Matrix of transmission line Susceptances
load	Load of system buses
М	Matrix of mapping the generation units to system
111	buses
Ν	Specified total number of vehicles
$S_b$	Base power of the system
Η	Incremental heat rate value in every step
$e_u$	$CO_2$ emission rate of unit
α	Importance factor for urban area emission
<u>Pg</u>	Unit minimum production limit

$\overline{Pg}$	Unit maximum production limit
Y	Line susceptance
s(l)	Sending end of transmission line
r(l)	Receiving end of transmission line
<u>F</u>	Transmission line minimum power limit
$\overline{F}$	Transmission line maximum power limit
fc	Fuel cost of generation units
Ω	Probability of every scenario

## **1. INTRODUCTION**

During 2012, annual global CO<sub>2</sub> emissions increased by 1.2%, reaching to a staggering 31.7 Gt. In this year, transportation sector was responsible for 23% of total CO2 production and almost three-quarters of this share was due to road transport [1]. Therefore, reducing the carbon intensity of passenger vehicles could have a large effect on reducing global CO<sub>2</sub> emissions. Electric vehicles (EVs) are believed to be the most suitable option for this purpose. During the years, EVs technology developed dramatically and governments conducted different plans to further grow EV usage. These efforts are paying off and global EV sales has doubled between 2011 and 2012 [2]. But this rapid growth rises another concern: What happens to electricity grids which are going to feed this new enormous load? Can they handle large amounts of EVs that are expected to hit the roads in the near future?

The impact of EVs on electricity grids has been the subject of many researches recently. Some of the researches are focused on the economic impacts of EVs on electricity grid such as [3], [4]. Kiviluoma and Meibom [5] analyzed the effect of EVs on Finland power system and concluded that "smart" charging can save 227€vehicle/year compared to "dumb" charging. Lyon et al. [6] showed that despite saving billions of dollars, smart charging cannot compensate its essential infrastructure cost. Fernandes et al. [7] estimated the impacts of EVs on a system with different levels of renewable energy penetration. They concluded that cooptimizing the electricity and EVs can cover the intermittency of renewable energy sources and cause more savings for the grid.

Technical impacts of EVs has been studied in several papers. Clement-nyns et al. [8] investigated the impacts of EVs on IEEE 34 bus test feeder and concluded that uncoordinated charging can cause distribution transformers to overload if the penetration level of EVs is high; although coordinated charging can prevent any damage to system. Shafiee et al. [9] developed a model to investigate PHEV impacts on residential distribution systems. Results of this paper show that voltage profile will hardly suffer from PHEVs but losses and peak load will increase dramatically with PHEV penetration level. Authors of this paper concluded that it is necessary to control the charging time of PHEVs in order to protect the distribution system from being damaged by the increased load. Impacts of EVs charging load on typical British distribution feeders are analyzed in [10]. It is showed that when the number of vehicles are high, distribution transformer and primary cables need to be strengthen to meet the increased load. Otherwise they would be badly overloaded. Effects of EVs on distribution transformers aging are evaluated in [11] and [12]. It has been concluded that large number of EVs with uncontrolled charging can severely damage transformers and reduce their lifetime.

EVs are mainly favored due to less fossil fuel usage, but the fuel they use, which is electricity, is also generated mostly by combustion of fossil fuels in power plants. Therefore, the anticipated environmental benefits from EVs, may not be as much as expected; and highly depend on the circumstances of the grid supplying them. Many researches have been done to evaluate the effect of a large EV fleet on power grid emissions. McCarthy and Yang [13] used an hourly electricity dispatch model to simulate the California power system response and determine its "marginal electricity mix" with the presence of EVs. Simulation results show that although being supplied by inefficient gas-fired power plants, EVs can reduce the overall CO<sub>2</sub> compared to CVs. But the difference is not that much in short term. Environmental impacts of EVs in the state of Ohio are evaluated comparing controlled and uncontrolled charging in [14]. Results indicate that although smart charging can successfully shift the charging time to low-load periods and decrease the costs, the controlled charging yield to higher emissions compared to uncontrolled charging, since Ohio has large number of coal-fired inexpensive power plants. Wu et al. [15] studied the effects of vehicle electrification in three developed regions in china. Authors conclude that plug-in hybrid electric vehicles (PHEVs) and pure electric vehicles (PEVs) may rise emission levels in highly carbonized power systems, and hybrid electric vehicles (HEVs) are suggested as the best option in these situations.

To deal with the mentioned operational and environmental impacts of EVs on power system, most of researchers have focused on "Smart Charging". Fan [16] borrowed the concept of congestion pricing in internet traffic control and used it to create a demand response framework to manage PHEVs. Smart charging is used to smooth out the load variance in a single household in [17]. Nguyen and Le [18] have co-optimized EV and home smart energy schedule to achieve minimum total energy cost of the household. In several researches, smart charging is used to cover the uncertain nature of renewable energy sources. It was shown in [19] and [20] that EVs smart charging can help grids to further employ wind farms. Birnie [21] investigated the possibility of charging EVs with solar panels during daytime by using smart charging. A few other approaches that are used in papers include reinforcement of distribution system [10] and allocating distributed generation sources [22].

The smart charging-based approaches have two major concerns: first, they may lead to short term operational solutions for only existing EVs. Hence, they may not guaranty a long term solution considering EVs and network growth. Second, smart charging essentially requires smart grid infrastructure, which may not be available in many cases. Besides the rapid growth of EV penetration in power systems, long term solutions for mitigating the operational and environmental effects of EVs seems to be essential. In other words, developing a long term approach for planning the EVs, regarding their different types and their different technical and environmental characteristics, in power systems may resolve the short term operational and environmental issues.

In this paper, we introduce a different approach to mitigate the operational and environmental impacts of EVs on power systems. The main purpose of the proposed approach is to develop a planning strategy for penetration of EVs in power systems, with the aim of reducing their environmental and operational impacts. In order to consider power system operational constraints and separate economical and environmental issues, the proposed planning approach is formulated through a bilevel optimization model. The objective of this model is to minimize the total CO<sub>2</sub> production from both EVs and generation units and is constrained to power system security through optimal power flow equations. Therefore, the output plan is going to minimize the environmental and technical impacts of EVs on the power system. By using bilevel optimization model, the method is capable of including smart charging, through its lower-level problem.

Another feature that distinguishes this approach, is using the technical differences between EV types. There are several types of EVs with different and sometimes contradictory characteristics. By optimally determining the share of every EV type, their characteristics will be combined and result in a better solution than single EV type approaches. Also a coefficient have been introduced to represent various priorities regarding reducing urban area emission.

The rest of this paper is organized as follows: in Section 2, characteristics of different EV types and their effect on power system is described. Section 3 contains the formulation and description of the proposed method. The case study is demonstrated in Section 4 and section 6 represents the concluding remarks

### 2. CHARACTERISTICS OF ELECTRIC VEHICLES

The proposed method in this paper utilizes the characteristics difference between EV types to minimize emissions. So, a brief description of EV types and their characteristics is essential for better understanding the equations in the next section. There are three main EV types are used in this paper:

#### 2.1. Pure Electrice Vehicles

Pure Electric vehicles or PEVs (some papers refer to them as BEV), rely only on electricity to run. They use electric motors for traction and batteries as energy source. Lack of fossil fuel combustion gives them important advantages over CVs such as absence of emissions, independence from petroleum and smooth and quiet operation. However, limited driving range and relatively low performance are their most important weakness, which held them back during 20th century [23].

PEVs should have large battery packs in order to achieve a reasonable driving range. This causes the

battery chargers to have high power consumption rating. Because the charging time should not take longer than the period in which, the car is parked at home.

Relevant specifications of EVs to this study, are their  $CO_2$  and electricity consumption. As mentioned before, PEVs consume large amounts electricity but do not produce GHG directly. The amount of electricity that a PEV consumes from the batteries while running, is calculated using (1).

$$demand_{pev} = \frac{d}{R_{pev}} bc_{pev}$$
(1)

As can be seen in (1), it is assumed that the energy consumption of PEVs, is linearly proportional to trip distance; and the effects of driving conditions are neglected.

## 2.2. Hybrid Electric Vehicles

Hybrid Electric vehicles or HEVs are the combination of PEVs and CVs. They use both electric motor and internal combustion engine (ICE) for traction; and have batteries in addition to fuel tank. Thus, they have the advantages of both PEVs and CVs and overcome their disadvantages.HEVs characteristics are in contrast with PEVs; they do not consume electricity form the grid, but produce GHG. In fact, from the viewpoint of this paper, their characteristics are mostly identical to CVs. They just consume less fuel, and hence produce less GHG. The amount of  $CO_2$  that an HEV produce in one day is calculated according to (2).

$$e_{HEV} = CPK_{HEV} \cdot d \tag{2}$$

## 2.3. Plug-In Hybrid Electric Vehicles

As the name suggests, a Plug-In Hybrid Electric Vehicle or PHEV, is an HEV which can be plugged into the grid. Unlike HEVs, battery is not a temporary energy source in PHEVs. So, the batteries in a PHEV are larger than an HEV, but not as large as the ones in a PEV.

There are two main operation modes for PHEVs: charge-sustaining(CS) mode and charge-depleting(CD) mode. In CS modes, the vehicle uses electricity and gasoline alternatively in order to maintain the state-ofcharge (SOC) of the batteries in a predefined region. But in CD mode, the vehicle uses the electricity until the batteries get depleted, and then switch to gasoline. The distance that a PHEV can run on CD mode is called "All-Electric Range" or AER. The AER of a PHEV is usually enough for one-day trip distances. Which means that if the vehicles are fully charged at the beginning of the day, which is the case in this paper, PHEVs and PEVs behave very similarly from the aspect of this study. But the ability to run on gasoline or any other fossil fuel adds great level of flexibility and reliability compared to a PEV; and overcomes the low driving range disadvantage of PEVs.

In this paper, it is assumed that PHEVs always operate in CD mode. So,  $CO_2$  from a PHEV in one day can be calculated by:

$$e_{phev} = \begin{cases} 0 & \text{if } d < AER \\ (d - AER)CPK_{phev} & \text{if } d > AER \end{cases}$$
(3)

As (3) states, if d is less than the AER of PHEV, then the vehicle doesn't consume any fuel, hence doesn't produce CO<sub>2</sub>. But if d exceeds the AER, the vehicle will consume fuel and emit CO<sub>2</sub> linearly proportional to the extra distance. The same happens for energy consumption of a PHEV in one-day trips:

$$demand_{phev} = \begin{cases} \frac{d}{AER} bc_{phev} & \text{if } d < AER \\ bc_{phev} & \text{if } d > AER \end{cases}$$
(4)

Regarding (4), if trip distance is less than AER, the amount of energy consumed from batteries is proportional to  $bc_{phev}$ . But if trip distance is more than AER, the vehicle consumes all its stored electricity and use fossil fuel to cover the remaining distance. So the total electrical energy that the batteries need to be fully charged again, is equal to their capacity.

# **3. PROPOSED METHOD**

In this paper, both the environmental and technical impacts of EVs on power system is addressed by optimally determining the share of every vehicle type. This optimization relies on the differences between EV types.

## 3.1. Assumptions

The problem which is addressed in this paper is consist of numerous influencing parameters. In order to avoid the overwhelming complexity, and to emphasize on the idea of the method, some assumptions has been made:

- Vehicles can only be charged in the driver's residence and after the last daily trip.
- It is assumed that vehicles will be fully charged and start the next day with full batteries.
- The charging session is assumed to be continuous.
- Each individual hour is divided into 10 minutes periods to consider short charging session which take less than an entire hour.
- All the vehicles are assumed to travel the same distance.

# 3.2. Method Formulation

In the proposed method, the decision making process is formulated as a bilevel optimization. The upper-level problem, shown in (5) to (8), represents the decisions to be made by the planner to achieve minimum  $CO_2$ generated by both the electricity and transportation sector. The lower-level problems, shown in (9) to (19), represent optimal power flow for each scenario and consider the EVs share and location known. The dual variables are provided after their corresponding equalities and inequalities separated by a colon:

$$\min_{x} \sum_{w \in \mathbf{W}} \Omega_{w} \Big[ \sum_{u \in \mathbf{G}} [e_{u} \sum_{t \in \mathbf{T}} \sum_{b \in \mathbf{B}_{u}} (Pg_{u,t,b,w}H_{u,b})] \\ + \alpha \sum_{i \in \mathbf{B}} (x_{i,phev}e_{phev,w} + x_{i,hev}e_{hev,w}) \Big]$$
(5)

subject to:

$$\sum_{i \in \mathbf{B}} (x_{i,hev} + x_{i,phev} + x_{i,pev}) = N$$
(6)

$$EVload_{i,t,w} = x_{i,phev} L_{phev,t,w} + x_{i,pev} L_{pev,t,w} \quad \forall i,t,w \quad (7)$$

$$x_i \ge 0 \quad \forall i \tag{8}$$

where

1

$$Pg_{u,t,b}$$
  $\forall u,t,b,w \in$ 

$$\arg\left\{\min_{P_{g,\delta,F}} \sum_{u\in\mathbf{G}} \left[fc_u \sum_{t\in\mathbf{T}} \sum_{b\in\mathbf{B}_u} \left(Pg_{u,t,b,w}H_{u,b}\right)\right] (9)\right\}$$

$$\sum_{u \in \mathbf{G}} M_{i,u} \sum_{b \in \mathbf{B}_{u}} Pg_{u,t,b,w} - S_{b} \sum_{j \in \mathbf{B}} B_{i,j} \delta_{j,t,w}$$

$$= load_{i,t} + EV load_{i,t,w} \qquad : \lambda_{bal}(i,t,w) \quad \forall i,t$$
(10)

$$-Pg_{u,t,b,w} \ge -\overline{Pg}_{u,b} \qquad : \overline{\lambda}_p(u,t,b,w) \quad \forall u,t,b \qquad (11)$$

$$\sum_{b \in \mathbf{B}_{u}} Pg_{u,t,b,w} \ge \underline{Pg}_{u} \qquad : \underline{\lambda}_{p}(u,t,w) \quad \forall u,t \qquad (12)$$

$$\delta_{i,t,w} \ge -\pi \qquad : \underline{\lambda}_{\delta}(i,t,w) \quad \forall t, i \mid i \neq slack \qquad (13)$$

$$-\delta_{i,t,w} \ge -\pi \qquad : \overline{\lambda}_{\delta}(i,t,w) \quad \forall t, i \mid i \neq slack \qquad (14)$$

$$\delta_{i,t,w} = 0 \qquad \qquad : \lambda_{slack}(t,w) \quad \forall t, i \mid i = slack \qquad (15)$$

$$F_{l,t,w} = S_b Y_l(\delta_{s(l),t,w} - \delta_{r(l),t,w}) \quad : \lambda_{line}(l,t,w) \quad \forall l,t \quad (16)$$

$$F_{l,t,w} \ge \underline{F}_l \qquad : \underline{\lambda}_F(l,t,w) \quad \forall l,t \qquad (17)$$

$$-F_{l,t,w} \ge -\overline{F}_{l} \qquad : \overline{\lambda}_{F}(l,t,w) \quad \forall l,t \qquad (18)$$

$$Pg_{u,t,b,w} \ge 0 \quad \forall u,t,b \} \forall w \tag{19}$$

The objective function of the upper-level problem, shown in (5), consists of the emissions caused by EVs power consumption (first line of (5)) and emissions caused by their fuel combustion (second line of (5)). In the second line of (5),  $\alpha$  is a new coefficient that represents the priority of reducing urban area emissions. Equation (6) states that the total number of EVs should be constant, since the reason behind vehicle usage is transportation needs, not power system requirements. Therefore, the total number of vehicles should be specified and fixed in this optimization. Also CVs are not included in the optimization, as their characteristics are similar to HEVs from the aspect of this research. The extra load which is added to power system due to EVs charging is calculated in (7). This load is included in the lower-level problem, in (10). The main decision variable of the upper-level problem is the share of EV types,  $x_i$ .

The upper-level problem is constrained by a collection of lower-level optimal power flow problems,

representing power system operation considerations for each scenario.

As it can be seen, both upper-level and lower-level problems are linear. Thus the lower-level problem can be represented by its constraints, its dual problem constraints and the strong duality condition [24],[25]. The dual of the lower level problem for scenario w is formulated in (20) to (30). The strong duality condition is formulated in (31).

$$\max_{\lambda} \sum_{i \in \mathbf{B}} \sum_{t \in \mathbf{T}} \lambda_{bal}(i, t, w) (load_{i,t} + EVload_{i,t,w}) + \sum_{u \in \mathbf{G}} \sum_{b \in \mathbf{B}_{u}} \overline{Pg}_{u,b} \sum_{t \in \mathbf{T}} \overline{\lambda}_{p}(u, t, b, w) + \sum_{u \in \mathbf{G}} \underline{Pg}_{u} \sum_{t \in \mathbf{T}} \underline{\lambda}_{p}(u, t, w) - \pi \sum_{\substack{i \in \mathbf{B} \\ i \neq slack}} \sum_{t \in \mathbf{T}} \left( \underline{\lambda}_{\delta}(i, t, w) + \overline{\lambda}_{\delta}(i, t, w) \right) - \sum_{l \in \mathbf{L}} \left[ \overline{F_{l}} \sum_{t \in \mathbf{T}} \overline{\lambda}_{F}(l, t, w) + \underline{F_{l}} \sum_{t \in \mathbf{T}} \underline{\lambda}_{F}(l, t, w) \right]$$
(20)

Subject to:

$$-S_{b}\sum_{j\in\mathbf{B}}[B_{j,i}\lambda_{bal}(j,t,w)] - S_{b}\sum_{\substack{l\in\mathbf{L}\\i=r(l)}}[Y_{l}\lambda_{line}(l,t,w)] + \underline{\lambda}_{\delta}(i,t,w) - \overline{\lambda}_{\delta}(i,t,w)$$

$$+S_{b}\sum_{\substack{l\in\mathbf{L}\\i=s(l)}}[Y_{l}\lambda_{line}(l,t,w)] = 0 \quad \forall t, w, i \mid i \neq slack$$

$$(21)$$

$$S_{b} \sum_{\substack{l \in \mathbf{L} \\ i=s(l)}} [Y_{l} \lambda_{line}(l,t,w)] - S_{b} \sum_{\substack{l \in \mathbf{L} \\ i=r(l)}} [Y_{l} \lambda_{line}(l,t,w)] - S_{b} \sum_{j \in \mathbf{B}} [B_{j,i} \lambda_{bal}(j,t,w)]$$
(22)

$$+\lambda_{slack}(t,w) = 0 \quad \forall t,w,i = slack$$

$$\underline{\lambda}_{F}(l,t,w) - \overline{\lambda}_{F}(l,t,w) - \lambda_{line}(l,t,w) = 0 \quad \forall l,t,w \quad (23)$$

$$\sum_{i=1}^{nb} M_{i,u} \lambda_{bal}(i,t,w) + \underline{\lambda}_{p}(u,t,w)$$
(24)

$$-\lambda_p(u,t,b,w) \leq fc_u H_u, b \quad \forall u,t,b,w$$

 $\overline{\lambda}_{p}(u,t,b,w) \ge 0 \quad \forall u,t,b,w$ (25)

$$\underline{\lambda}_{p}(u,t,w) \ge 0 \quad \forall u,t,w \tag{26}$$

$$\overline{\lambda}_{\delta}(i,t,w) \ge 0 \quad \forall i,t,w \tag{27}$$

$$\lambda_{\delta}(i,t,w) \ge 0 \quad \forall i,t,w \tag{28}$$

$$\overline{\lambda}_F(l,t,w) \ge 0 \quad \forall l,t,w \tag{29}$$

$$\underline{\lambda}_{F}(l,t,w) \ge 0 \quad \forall l,t,w \tag{30}$$

In order to avoid complexity, it is assumed that vehicles' charger power is equal to their rated power and does not change during charging period. Therefore, the needed charging time for a PEV or PHEV is simply calculated by dividing the consumed energy from batteries by the chargers rated power according to (32) and (33), respectively.

$$\sum_{u \in \mathbf{G}} [fc_u \sum_{t \in \mathbf{T}} \sum_{b \in \mathbf{B}_u} (Pg_{u,t,b,w} H_{u,b})] = \\ + \sum_{u \in \mathbf{G}} \sum_{b \in \mathbf{B}_u} \overline{Pg}_{u,b} \sum_{t \in \mathbf{T}} \overline{\lambda}_p(u,t,b,w) \\ + \sum_{u \in \mathbf{G}} \underline{Pg}_u \sum_{t \in \mathbf{T}} \underline{\lambda}_p(u,t,w) \\ + \sum_{i \in \mathbf{B}} \sum_{t \in \mathbf{T}} \lambda_{bal}(i,t,w)(load_{i,t} + EVload_{i,t,w}) \\ - \sum_{l \in \mathbf{L}} [\overline{F}_l \sum_{t \in \mathbf{T}} \overline{\lambda}_F(l,t,w) + \underline{F}_l \sum_{t \in \mathbf{T}} \underline{\lambda}_F(l,t,w)] \\ -\pi \sum_{\substack{i \in \mathbf{B} \\ i \neq slack}} \sum_{t \in \mathbf{T}} \left( \underline{\lambda}_{\delta}(i,t,w) + \overline{\lambda}_{\delta}(i,t,w) \right)$$
(31)

$$T_{pev,w} = \frac{demand_{pev,w}}{C_{pev}} \quad \forall w$$
(32)

$$T_{phev,w} = \frac{demand_{phev,w}}{C_{phev}} \quad \forall w$$
(33)

Therefore, the charging load for every time period for an individual PEV and PHEV is calculated using (34) and (35) respectively:

$$L_{pev,t} = \begin{cases} C_{pev} & for & t \le \begin{bmatrix} T_{pev} \end{bmatrix} \\ 0 & for & t > \begin{bmatrix} T_{pev} \end{bmatrix} \end{cases} \quad \forall w \quad (34)$$

$$L_{phev,t} = \begin{cases} C_{phev} & for & t \le \lfloor T_{phev} \rfloor \\ 0 & for & t > \lfloor T_{phev} \rfloor \end{cases} \quad \forall w \quad (35)$$

## 4. CASE STUDY

#### 4.1. Input data

In this paper, vehicle data is obtained from real world EVs which are the best sellers in their category [26]. Table 1 summarizes the vehicle specifications using the data in [27], [28], [29] and [30].

Table 1: Vehicle Specifications

Name	Туре	CPK (kgCo <sub>2</sub> /mile)	bc (kWh)	R (mile)	C (kW)
Toyota Prius	HEV	0.177	-	-	-
Nissan Leaf	PEV	-	24	84	6.6
Chevy Volt	PHEV	0.240	17.1	38	4

IEEE RTS 24 bus system is used in this paper for case study, as it has different generating unit types; which is a suitable option for the propose of this study. In order to analyze the worst case scenario, the vehicles are assumed to be charged at system peak hours. Also, daily vehicle driving data are obtained from [31], [32].

## 4.2. Simulation results

In this section, the simulation results are presented for different values of  $\alpha$ , as it is the most important decision factor in the model. Total number of vehicles are assumed to be 83000 since the system cannot handle more EV, specially PEVs during its peak hours.

Figure 1 shows the share of every vehicle type for different values of  $\alpha$ . As it can be seen in this chart, when the value of  $\alpha$  is low, HEVs are preferred, but as  $\alpha$ increases, HEVs lose their dominance and share, and PEVs become better options. This happens because of high carbon intensity of generated electricity in the studied system. Figure 2 helps to better understand this. In this figure, total emission of the optimum plan, generated by the proposed model is compared to the situations where only one type of EVs is used. It can be observed in this chart that, when  $\alpha$  is low, HEVs produce much less total emission than the other two types. As a result, they dominate the share. by increasing the value of  $\alpha$ , total emission of PEVs stay unchanged as they don't produce emission in the city, but total emission of HEVs grow and become comparably close to PEVs, and in some point ( $\alpha$ =1.6) HEVs curve crosses the PEVs and become larger. Consequently, by increasing the priority of reducing emission in cities, share of PEVs, that don't use fossil fuel, grow bigger. Figure 2 also shows that the proposed method is successfully reaching to the minimum total emission, for every value of  $\alpha$ .

Another important point in Figure 1 is the absence of PHEVs. PHEVs have great degree of flexibility due to their characteristics and structure, therefore, they are expected to gain a solid share among other EV types, but the simulation results show the opposite. Figure 2 partially explains this issue. In this figure, it is obvious that the total emission of PHEVs are far greater than the two other types. Therefore, the method is correctly omitting them from the optimum share. The reason behind this huge amount of emission lies in the lower efficiency of the PHEV model that is used in the simulations. By comparing EV types specification in Table 1, it can be noticed that the PHEV has less efficiency in both electric and fuel consuming modes. Therefore, in order to evaluate the role of the general characteristics of EV types, and prevent the specifications to interfere with the results, PHEV specifications are altered in way that its efficiency match the two other types. The new specifications are listed in

By using the improved PHEVs, the simulation results show that PHEVs would have a noticeable share, as displayed in Figure 3. like the previous case, when the importance of reducing urban emission is low, HEVs are better options because of the high carbon emission of electricity production. But as  $\alpha$  increase, PHEVs gain a dominant share. This is expected as PHEVs characteristics are the combination of PEVs and HEVs. Further increasing of  $\alpha$  makes the benefits of PHEVs fade out as the main focus shifts to reducing the emission in the cities. Figure 4 better explains this. It can Table 2: Modified PHEV Specifications

	CPK (kgCo <sub>2</sub> /mile)	bc (kWh)
Modified PHEV	0.177	11
Original PHEV	0.240	17.1



Figure 1: share of EV types



Figure 2: Total emission of the optimal plan compared to single vehicle plans



Figure 3: share of EV types with modified PHEV



Figure 4: Total emission of the optimal plan compared to single vehicle plans with modified PHEV

be observed in this figure that PHEVs produce less emission than PEVs, and as a result, have a bigger share in the optimum plan. Notice that the proposed method, is successfully minimizing total emissions again as well as the previous simulation.

### **5.** CONCLUSION

In this paper, the potential impacts of EVs on power system were addressed through an optimization-based method which utilizes the differences between electric vehicles specifications. Three types of EVs were employed in this paper including PEVs, PHEVs and HEVs. The proposed method optimally determine the share of EV types in every bus of the power system in a way that the total CO<sub>2</sub> emission from transportation and electricity generation sectors are minimized. The proposed method also maintains the operation of the power system in its secure limits using OPF. The method is formulated as a bilevel programing model in order to separate environmental and operational considerations. By using duality theory, the model is reduced to a singlelevel optimization model. A new coefficient is introduced to model different priorities in reducing urban area emissions.

In order to show the methods capability, a case study is executed on the IEEE 24 Bus Reliability Test System, using real-world vehicle data. Results showed that the proposed method successfully minimize total emissions caused by electric vehicles, compared to single vehicle approaches. The introduced decision factor,  $\alpha$ , was found to work as it was expected and had significant effect on results. It was also observed that, due to high carbon intensity of electricity generation, if the priority of reducing urban area emissions is low, using PEVs, which consume grid electricity is not a suitable option, as they increase total emissions. In other words, electricity generation facilities produce more carbon, emissions compare to HEVs. Therefore, as long as emission in cities haven't reached critical levels, using HEVs would be the best solution to global CO<sub>2</sub> emissions. However, if the priority of reducing emission in cities is high, using PEVs would be a better choice, although they increase total emissions. Results also show that the efficiency of vehicles have great influence on the optimum plan, since original PHEV had no share in the optimum plan, but the modified PHEVs had significant share in the optimum plan.

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