Three Players Nash Equilibrium Game Concerning the Charging Time and Place of Employee Electric Vehicles

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ABSTRACT

In this study, we model the demand for and supply of charging facility at workplace, and the associated consequences on social welfare. We found that both employers and workers benefit from the accessibility of workplace charging when: i) they agree to pay for workplace charging out of gross salary and when the labor tax is high; ii) employers pay less electricity tariff than households do; iii) the employment contract duration is long; iv) recharging electric vehicles (EVs) takes longer time and the value of time is higher. Accessibility of cheaper charging facility at workplace, while saves the charging time and increases the share of EVs as commuting mode, it results in unintended consequences including electricity peak-load problem, an increase in electricity tariff for household use, and an increase in car use that worsens traffic congestion. For the electricity supplier, workplace charging increases the cost of supplying electricity by aggravating the daytime peak-load problem and by increasing the demand variation from the mean. Tax based on yearly travel distance, and restriction on free workplace charging access improves social welfare. The results from this study are relevant in (i) helping to predict the choice of time and place of charging of employees' EVs, (ii) supporting employers to understand the implications of workplace charging provision, (iii) providing electricity suppliers with information for correct electricity demand predictions, and (iv) revealing to policy makers the non-taxed fringe benefit problem of charging at the workplace.

Keywords: Electric Vehicle, Workplace Charging, Employee, Employer, Electricity Supplier

1. INTRODUCTION

Even though the current market penetration rate of electric vehicles (EVs) is sluggish, they are expected to become a staple of commuting in the near future. While residential charging is the foreseen primary option, workplace charging opportunities are experiencing rapid growth and gaining increasing attention as the major secondary option. Government and state initiatives support this growth, for example, the U.S. Department of Energy has been offering subsidies to employers who launch workplace charging programs (Calstart, 2013). The rationale for subsidizing workplace charging has been to increase the sale of EVs by promoting early adoption with the aim of reducing pollutant emissions from automobiles and curtailing dependence on fossil fuels.

Increasing sales of EVs would translate into increasing numbers of EV commuters that could motivate employers to provide charging facility at workplace for at least four reasons. Firstly, charging facility provision at the workplace can be a recruitment and retention tool. When the share of EV commuters increases, employers that provide charging facility have a better chance of attracting employees than employers that do not provide, ceteris paribus. secondly, charging facility provision at the workplace would provide opportunity for green corporate branding, at least in the short-run before most employers offer charging facility, and consequently to increase the incentive of consumers towards buying outputs from employers having EVs charging because of their green ideas. Lastly, it could serve as gain tax benefits and to reduce the operational costs of company-owned vehicles.

Empirical findings exist to support the four aforementioned reasons for employers to provide workplace charging. Higher labor productivity was observed for employers that adopted high environmental standards because employees increased their efforts when working for companies that are socially responsible (Delmas and Pekovic, 2013; Lanfranchi and Pekovic, 2014). The same high environmental standards were found also responsible for better employee recruiting (Grolleau et al., 2012), increased sales and profits (Grolleau et al., 2013) and job satisfaction and creativity (Spanjol et al., 2014). Corporate social responsibility from a more general perspective was found related to employees accepting lower wages and working more unpaid hours (Burbano, 2014). Similarly, green companies were shown to have potential to reduce the moral hazard problem and to recruit workers at lower wages than non-green firms (Brekke and Nyborg, 2008). Clearly, charging facility provision is an opportunity for company branding with the aforementioned opportunities to recruit productive employees and motivate them to increase productivity to reduce taxes and not to inflate wage rates. Nonetheless, working charging provision comes with installation, maintenance and electricity costs that the employers would need to evaluate.

From the employee perspective, accessibility of charging facility at the workplace would provide a handful of benefits. Firstly, workplace charging provision would help to reduce the driving range anxiety problem currently affecting EV users because of the low driving ranges causing drivers to be afraid not to reach their destination before the battery runs out. Secondly, employees could pay for the workplace charging from their gross salary in that they save tax, similarly to untaxed fringe benefits such as employer-paid parking and company car (Shoup, 1997; Van Ommeren et al., 2006). Thirdly, workplace charging could save valuable time with respect to charging at alternative stations (e.g., commercial stations, public stations) that could be used by employees for generating income or enjoying leisure. Moreover, workplace charging could imply savings even in the case they pay, since companies often have more favorable electricity tariffs than households (IEA, 2012). In this respect, it is important to consider the electricity supplier's perspective, as increasing sales of EVs and consequent increasing workplace charging provision could result in grid overload during working hours. However, electricity suppliers might provide attractive rates for employers while recovering the associated overload cost by increasing the tariff on the relatively price inelastic customers, households.

Although advantages are observed for employers and employees, disadvantages exist to the workplace charging provision. The shortcomings of transport related fringe benefits in terms of travel demand, traffic congestion and car use have been observed in the literature. Employer-paid parking has been illustrated to lead to higher car use and reduced car sharing (De Borger and Wuyts, 2009; Shoup, 1997). Company-car tax reductions have been demonstrated to lead to higher travel demand (Shiftan et al., 2012). Similar disadvantages could materialize with workplace charging provision. Firstly, the electricity overload problem could be aggravated in the case that EV commuting employees could start charging at the workplace as their primary option, thus increasing electricity consumption during the peak hour. Secondly, workplace charging provision could affect significantly traffic congestion as the employees could increase car use since the charging fee and the value of time of charging EVs at commercial/public charging stations will decline. Thirdly, the electricity price for the general population could increase because of the aforementioned load increase and since the households' electricity demand is price inelasticity. Lastly, residential location of employees could be affected in the case that the employers pay for EV charging as there would be a lower incentive to reduce commuting distances since commuting will become relatively cheaper.

Given the existing knowledge about workplace charging provision and considering the related advantages and disadvantages from the perspectives of the agents involved, it is clear that the literature did not address the effects of EV commuting and workplace charging provision on the surpluses of employees, employers and electricity suppliers as well as on social welfare. This study presents a theoretical model to analyze these effects by representing the incentives for and the costs of workplace charging provision for the three agents. This study derives the best strategy for each agent under the assumption of acting only for their own benefit, and then uses the model to investigate analytically the economic inefficiencies that could result from the interaction of the three agents. Lastly, this study looks at policy options to curtail the resource distortion.

The remainder of this paper is organized as follows. Section 2 presents the framework of the model from the perspectives of the three agents (i.e., employee, employer, electricity supplier) followed by section 3 presenting the changes on surpluses of the three agents arising from workplace charging accessibility along with policy options for social optima. Section 4 presents the conclusions in terms of policy instruments and introduces further research directions.

2. MODEL FRAMEWORK: THE THREE AGENTS' PERSPECTIVES

We consider consumer (employee) who maximizes expected utility by optimally allotting resources over consumption of general goods and service, leisure time, and travel. We assume that the consumer already made car choice decision, and has an EV as the only private car. The EV can be charged at home, at workplace and/or at commercial and public charging stations. We assume that there is no queue for charging at home and at workplace, implying that there is no wastage of valuable time for recharging at these locations; whereas, there is a possibility of queueing and the consumer has to spend some time to recharge the EV at commercial and public places since recharging EVs takes time. Thus, the employers´ demand for charging access at workplace could emanate from the incentive to save recharging time of charging at commercial charging stations, and to save charging fee in the case that the charging fee at workplace is cheaper. For charging at workplace, the employee could to pay in terms of reduction on gross salary, per unit fee or a combination of the two, or even may get free charging. On the other hand, employers' objective is assumed to be to minimize the cost of producing a target level of output. The employer uses per unit fee and/or deduction on gross salary to indirectly influence the cost minimizing share of EV-commuters who are to be offered charging access at workplace. That is, the employer trades off between paying a market wage rate without providing charging access accepting any forgone benefit of providing charging access and providing charging facility for a lower wage and/or levying fee to cover the cost of charging facility provision and exercising any benefits from provision. We assume that both the output and labor market is competitive so that the firm is a price taker, but the firm can negotiate over gross salary with employees who are offered charging facility. The remainder of this section presents the model construction from the perspectives of the three agents.

2.1. The Employee's Perspective: The Demand for Workplace Charging

2.1.1. Cost and Location of Charging of Employees' EVs

Consider a working day for an EV-commuting employee. Denote by $\overline{w}(1\text{-}\tau)$ the market wage rate that the employee earns in the absence of charging facility at the workplace, and by $w^W(1\text{-}\tau)$ the wage rate with charging access, where $w^W \leq \overline{w}$. While charging EVs is a daily activity, we assume that, the decision whether to demand for (or accept an offer) charging access at workplace is a one time decision that the employee has to make, could be, at the time of employment or at other time when such issue is triggered. The employee takes, among other, the daily travel amount, charging fee differences among different locations (i.e., at home, at workplace and at commercial charging stations) and the risk of driving range limitation of the EV in to account while deciding for accessibility of charging at workplace. For charging access at workplace, the employee could pay from pocket money (i.e., from income after tax), from gross salary (i.e., from income before tax) as is the case for a number of fringe benefits, or receive free charging access from a benevolent employer.

Denote by D the daily expected travel amount of the employee and by d_0 the amount of battery loading level at the beginning of the day both in terms of distance units. Consider the travel cost being uncertain at the time the employee agrees with the employer about workplace charging provision, namely the uncertainty concerns whether the amount d_0 is enough to cover D. If $d_0 \geq D$, the employee does not need to recharge the EV during that day because the available battery loads covers the daily travel amount. We do not consider the analysis for the case that $d_0 \geq D$ since the result is trivial. If $d_0 < D$, the employee needs to recharge the EV or change commuting mode, and the reasons for the lack of battery load could be (i) that the employee has unforeseen trip(s) that require battery load higher than the one available, or (ii) that the employee has not the possibility of charging at home for technical failures or for forgetting to charge. For simplicity, we assume that the employee expects to charge at commercial/public charging stations with probability γ, and, thus, γ can be considered as the expected share of the number of days during the employment contract period that the employee expects to charge the EV at stations other than at home.

Consider the different travel costs to be experienced by the employee that depends on the choice of charging location: p^H, p^W and p^C, respectively, denoting the electricity tariff per distance unit equivalence for charging at home, at workplace and at a commercial/public charging station. Note that p^C can also be the per distance unit fee for using non-EV mode in case the employee is not using the EV. In the absence of charging facility at workplace, the employee’s travel cost per D units is p^H for charging only at home when $d_0 \geq D$ with probability ($1-\gamma$). Otherwise, the employee experiences both p^H and p^C. Denote by β the share of cost she (the employee) expects to pay for home charging, and ($1-\beta$) is the expected share of cost for charging at commercial charging stations. Thus, the daily expected price of charging per D units, denoted by c^H, in the absence of charging access at workplace is given by

$$c^H = (1-\gamma)\, p^H + \gamma(\beta p^H + (1-\beta) p^C) = dp^H + (1-d)\, p^C, \qquad (1.1)$$
$$\text{where } d = 1-\gamma + \gamma\beta$$

Thus, d is the expected share of charging fee for charging at home, and ($1-d$) is the expected share of fee the employee expects to pay for charging at workplace in the absence of charging access at workplace. When charging facility is accessible at workplace, the employee could extend the driving range of the EV and avoid charging at commercial charging stations by recharging at workplace. Moreover, if $p^W < p^H$, she saves money from charging by shifting part of the home charging to the workplace. For example, she could charge at home only the amount that secures the commuting to work and then charge at the workplace the amount needed for the remaining trips of the day. In the case that workplace charging is provided, the monetary cost of travel per D units on daily bases of a working day, denoted by c^W, is, thus, given by

$$c^W = \left(1-\alpha(p^W, p^H)\right) dp^H + \left(\alpha(p^W, p^H)\mathrm{d}+1-d\right) p^W, \tag{1.2}$$

where $\alpha(.)$ with $\alpha_1 = \dfrac{\partial\alpha}{\partial p^H} \geq 0$ and $\alpha_2 = \dfrac{\partial\alpha}{\partial p^W} \leq 0$ is the share of charging that the employee shifts from home to workplace to save cost when the latter is cheap.

By equation(1.2), we implicitly assume that the employee meets the expected travel demand *D* by charging at both home and at the workplace without the need for recharging at commercial charging stations.

Using equations (1.1) and (1.2), the expected monetary cost, c^i, of travel per *D* units, where the index *i* representing accessibility of charging at workplace being either accessible, *W* (we call this 'workplace charging'), or not accessible, *H* (we call this 'home charging'), is given by

$$c^i = \begin{cases} dp^H + (1-d)p^C & \text{for } i = H \\ (1-\alpha)dp^H + (\alpha d + 1 - d)p^W & \text{for } i = W \end{cases} \tag{1.3}$$

In addition to the monetary cost, traveling involves time for driving and for recharging the battery of the EVs. At least by assumption, recharging the EV at home and at workplace involves a costless time since the employee can do her work while the car is being recharged. Whereas, recharging at commercial charging stations implies additional time use for queuing to charging stations and for recharging. Denote by t_d the driving time per distance unit, and by t_c the recharging time per distance unit, where $t_c = 0$ for charging at home and at workplace. Then, the total expected travel and recharging time per *D* units, denoted by ${t_D}^i$, is given by

$${t_D}^i = \begin{cases} t_d + t_c(1-d) & \mathit{for}\ i = H \\ t_d & \mathit{for}\ i = W \end{cases} \tag{1.4}$$

Thus, accessibility of charging access at workplace saves the employee's time amounting $t_c(1-d)$, which is non-negative, and saves cost that equals $\alpha(p^H - p^W)\text{d}+(1-d)(p^C - p^W)$, the former term of which is very unlikely to be negative since the worker could otherwise charge at home, and the latter term could take any sign depending on the fee the employer levies relative to the fee at commercial/public charging stations.

The employee has a two-stage decision for utility maximization. In the first stage, the employee allots the monetary and time budget over consumption of general goods and services, leisure and travel. In the second stage decision, the employee chooses location of recharging the battery of the EV by reaching an agreement with the employer.

2.1.2. First-Stage Decision: Allocation of Budget for Utility maximization

A) When the Employee Pays from Pocket Money

Assuming that the worker pays from pocket money for charging at workplace, and that wage is the only source of income for the worker, the employee maximizes utility from consumption of general goods and services, *x*, leisure, *l*, and travel, *D*, given by

$$\max \quad U(x^i,\ l^i, D^i) \tag{1.5}$$

where *U*(.) is a well-behaved utility function.
The employee maximizes (1.5) subject to budget and time constraints given by

$$\begin{aligned} x &= \bar{w}(1-\tau)t_w{}^i - c^i D \\ l^i &= T - t_w{}^i - t_D{}^i D \end{aligned} \tag{1.6}$$

where the price of x is normalized to unity, t_w is time for wage-earning, T is the total time budget for a day, i is indicator of location of charging, and all other terms are as defined before.

After solving the time constraint for t_w plugging in to the budget constraint, we have a consolidated budget constraint equation given by

$$x + \bar{w}(1-\tau)l^i + \left(c^i + \bar{w}(1-\tau)t_D{}^i\right)D^i = \bar{w}(1-\tau)T \tag{1.7}$$

Thus, the Lagrangian equation for the utility maximization problem is given as

$$Z(\mathrm{x},l,\mathrm{D};\lambda)=U(x^{i},\ l^{i},D^{i})-\lambda^{i}\left(\bar{w}(1-\tau)l^{i}+\underbrace{\left(c^{i}+\bar{w}(1-\tau)t_{D}{}^{i}\right)}_{\rho^{i}}D^{i}-\bar{w}(1-\tau)T\right) \quad (1.8)$$

where *Z(.)* is the lagrangian function, $\bar{w}(1-\tau)T$ is the full income when the employee allots all time for wage-earning work, ρ^{i} is the generalized cost of traveling a unit of *D*, which is given by

$$\rho^{i}=\begin{cases} dp^{H}+\ (1-d)\,p^{C}+\left(t_{d}+(1-d)t_{c}\right)\bar{w}(1-\tau) & \text{for } i=H \\ \left(1-\alpha\right)dp^{H}+\left(\alpha d+1-d\right)p^{W}+t_{d}\bar{w}(1-\tau) & \text{for } i=W \end{cases} \quad (1.9)$$

The first order conditions for the utility-maximization problem and the corresponding demand functions for utility maximizing values of the consumption bundles are given as

$$\begin{aligned} &\frac{1}{\lambda}U_{x}=1, \qquad \frac{1}{\lambda}U_{l}=\bar{w}(1-\tau), \qquad \frac{1}{\lambda}U_{D}=\rho^{i} \\ &j^{i,*}=j^{i}(d,a,p^{i},p^{C},\bar{w}(1\text{-}t),t_{d},t_{c},g) \end{aligned} \quad (1.10)$$

Where λ is the Lagrangian multiplier from the consolidated budget constraint, U_{j} denotes the marginal utility from consumption bundle j, *j = x, l, D*, and i = W, H. Following the empirical literature, we assume that the demand for each of *x, l* and *D* is non-decreasing with income and non-increasing with own price.

Result 1.1. *Reservation prices for charging at workplace versus at commercial charging stations*: From the generalized cost of travel, i.e., (1.9), we can solve for the reservation price, $\overline{pW}$, that the employee will be willing to pay for charging at workplace instead of at commercial charging stations. Equating $\rho^{\mathrm{H}}=\rho^{\mathrm{W}}$, and solve for p^{W}, we have

$$\overline{pW}=\frac{1}{\alpha d+1-d}\left(\alpha p^{H}+(1-\mathrm{d})[pC+t_{c}\bar{w}(1-\tau)]\right) \quad (1.11)$$[1]

If $\alpha = 0$, i.e., if the employee's only incentive for demanding charging access at workplace is to save the charging time used for charging at commercial charging stations, not to save cost by shifting part of home charging to workplace, then equation (1.11) becomes

[1] The computation of $\overline{pW}$ is bases on a strict assumption that the value of a unit of charging time at commercial charging stations equals wage rate net of labor tax. In situations where this is not the case, for example, if waiting the car to be charged at commercial charging station involves disutility of being there, then p^{W} could be higher than the one stated above, and, on the other hand, if the worker uses the time of charging for working inside the car, shopping, etc., then p^{W} could be lower than the one given in (1.11).

$\overline{pW} = pC + t_c\bar{w}(1-\tau) > pC$. Thus, the employee is willing to pay more for charging at workplace than the charging fee at commercial charging stations, where the amount of the reservation price difference depending, among others, on the value of a unit of time and the duration of time it takes to recharging the EV at commercial charging stations.

For later use, let's write the indirect utility function in terms of the Lagrangian function at optimal choice using the envelope theorem (Wainwright, K., 2004: pp, 437), and derive some comparative statistic as follows.

$$Z^i(.) = V^i(\cdot) = U\left(x^{i,*}, D^{i,*}, l^{i*}\right) + \lambda^{i,*}\left\{\bar{w}(1-\tau)T - x^{i,*} - \rho^i D^{i,*} - \bar{w}(1-\tau)l^{i,*}\right\} \quad (1.12)$$

where $V^i(.)$ is the indirect utility function, the stars (*) denote utility maximizing values, and all other terms including $i = H, W$, are as defined before.

2.1.3. Second-Stage Decision: Location of Charging Place

In the second stage of the utility-maximization problem, the employee chooses the place of charging that maximizes utility. That is,

$$\max_i \ (V^H, V^W) \quad (1.13)$$

The employee prefers to charge at the workplace and demands for charging accessibility at workplace by negotiating over wage rate deduction, fee for charging and/or both if and only if $V^W \geq V^H$. Accordingly, the probability of charging at the workplace, denoted by θ, is given by

$$\theta = \Pr(V^W - V^H \geq 0) \quad (1.14)$$

Note that θ is a binary choice problem, from which, one can derive the demand for charging access at the workplace empirically using, for example, the standard choice models such as logit and probit for employees at large.

Result 1.2. *The share of employees' to demand charging access at workplace*: Assuming a uniform distribution of EV-commuting workers regarding the demand for charging access at workplace with a preference parameter ε with support [$-a,+a$] and mean zero (e.g., De Borger and Wuyts, 2011). Then the share of workers preferring charging at the workplace is given by

$$\theta = \frac{1}{2a}\left[a - \frac{1}{\lambda}\left(V^H - V^W\right)\right] \quad (1.15)$$

where θ is the share of EV-commuters preferring charging access at workplace, which equals the probability given in (1.14) under the assumption of uniform distribution of employees' preference for charging access at workplace.

2.1.4. Determinants of θ: Comparative Statistics

Note that, for any variable and parameter *k* in (1.12), we have

$$\text{sign}\left(\frac{\partial\theta}{\partial k}\right) \equiv \text{sign}\left(\frac{\partial V^W}{\partial k} - \frac{\partial V^H}{\partial k}\right) \tag{1.16}$$

Accordingly, we present some of the comparative statistics results concerning the effects of decision variables of the government (i.e., labor tax), the employer (p^W) and of the electricity supplier (i.e., p^H, p^C) as well as other exogenous variables on the probability of charging at workplace, each evaluated at the optimum choice.

Result 1.3. *Labor tax and the probability of charging at workplace*: *A higher labor tax decreases the probability of charging at workplace when the employee pays her reservation fee (i.e., the maximum willingness to pay) from pocket money for charging at workplace, ceteris paribus. That is,*

$$\left(\frac{\partial V^W}{\partial \tau} - \frac{\partial V^H}{\partial \tau}\right) = \lambda\bar{w}\left(t_w{}^H - t_w{}^W\right) \leq 0 \Rightarrow \frac{\partial\theta}{\partial\tau} \leq 0 \tag{1.17}$$

Proof: By applying the envelop theorem on equation (1.12) and using equation (1.9), we have

$$\frac{\partial V^W}{\partial \tau} = -\lambda^W \bar{w}\left[T - l^{W,*} - t_d D^{W,*}\right] = -\lambda^W \bar{w}(\mathrm{t_w}{}^{\mathrm{W}})$$

$$\frac{\partial V^H}{\partial \tau} = -\lambda^H \bar{w}\left[T - l^{H,*} - (t_d + t_c) D^{H,*}\right] = -\lambda^H \bar{w}(\mathrm{t_w}{}^{H})$$

where $\mathrm{t_w}^{\mathrm{H}}$ = T - $l^{H,*}$ - ($\mathrm{t_d}$+$\mathrm{t_c}$) $D^{H,*}$ and $\mathrm{t_w}^{\mathrm{W}}$ = T - $l^{W,*}$ - $\mathrm{t_d}$ $D^{W,*}$.

Note that charging access at workplace allows the employee to save time used to charge at commercial charging stations. However, the employee is paying her reservation price for charging at workplace implies that $V^H = V^W$ (, which, in turn, implies $\lambda^H = \lambda^W$), and that the generalized price of travelling is the same, i.e., $\rho^H = \rho^W$. Thus, the relative price of consumption bundles remains the same in the case that working hours are flexible[2] in that the employee uses the saved time for wage earning to pay for the increased monetary cost of travel. Given a well-behaved preference in that the optimal values of *x, l, D* are all positive, that the relative prices of *x, l, D* are unaffected, and that working hours are flexible, then accessibility of charging at workplace does not affect the optimal values of *x, l, D*. That is,

$$x^{W,*} = x^{H,*},\ D^{W,*} = D^{H,*} = \mathrm{D}^{*}\ \ \&\ \ l^{W,*} = l^{H,*} \tag{1.18}$$

Therefore, $t_w^W = t_w^H + t_c D^{H,*} \geq t_w^H$, and, thus, an increase in labor tax decreases the probability of charging at workplace when the effect is evaluated from $V^H = V^W$ the employee paying a reservation fee for charging at workplace. That is,

$\dfrac{\partial V^W}{\partial \tau} - \dfrac{\partial V^H}{\partial \tau} = \lambda \bar{w}\left(t_w^H - t_w^W\right) \leq 0 \,|_{V^W = V^W} \Rightarrow \dfrac{\partial \theta}{\partial \tau} \leq 0$. This completes the proof.

The result is intuitive. A higher labor tax means a lower opportunity cost of the time used to recharge the EV at commercial/public charging stations, which reduces the worker's incentive to demand (accept offer of) charging access at workplace.

Result 1.3. Charging fee at home and *the probability of charging at workplace*: *The effect of an increase on charging fee at home on the probability of workplace charging depends on the charging fee difference between home charging and workplace. If the fee for charging at home is higher than the fee for charging at workplace, i.e., if $p^H > p^W$, then the probability of workplace charging increases with p^H*; otherwise, the effect is negligible, *ceteris paribus. That is,*

$$\left(\frac{\partial V^W}{\partial p^H} - \frac{\partial V^H}{\partial p^H}\right) = \beta \lambda D^{*}\left(\alpha + \alpha_1 (p^H - p^W)\right) \geq 0 \Rightarrow \frac{\partial \theta}{\partial p^H} \geq 0 \text{ if } p^H \geq p^W \tag{1.19}$$

Proof: By applying the envelop theorem on equation (1.12), we have

[2] If working hours are fixed, i.e., $t_w^W = t_w^H$, then the employee cannot anymore afford ($x^{H,*}$, $D^{H,*}$) since the monetary cost of travelling increases though its generalized price remains the same. An increase in monetary cost of travelling (since $\overline{pW} > p^C$) induces the employee to substitute some of $D^{H,*}$ for *x*, implying that, at the new optimal, we have $D^{W,*} < D^{H,*}$ and also due to the income effect even though travelling becomes relatively cheaper in terms of time. The effect on the utility-maximizing value of *x* depends on the relative magnitude of the income and substitution effects, where $x^{W,*} > x^{H,*}$ if the substitution effect dominates the income effect, and vice versa. Whereas $l^{W,*} > l^{H,*}$ since the employee has the saved time, $t_c D^{H,*}$ and time from reduced travel, $t_d(D^{H,*} - D^{W,*})$.

$$\frac{\partial V^W}{\partial p^H} = -\lambda^W D^{W,*} d\left[(1-\alpha) - \alpha_1\left(p^H - p^W\right)\right]$$

$$\frac{\partial V^H}{\partial p^H} = -\lambda^H D^{H,*} d$$

$$\Rightarrow \frac{\partial V^W}{\partial p^H} - \frac{\partial V^H}{\partial p^H} = \lambda d D^*\left(\alpha + \alpha_1 (p^H - p^W)\right)\Big|_{V^W = V^H} \geq 0 \text{ if } p^H \geq p^W$$

Note that,

if $p^H < p^W$, then $\alpha \to 0 \,\&\, \alpha_1 \to 0$

$$\Rightarrow \frac{\partial V^W}{\partial p^H} - \frac{\partial V^H}{\partial p^H} \to 0, \text{ and thus, } \frac{\partial \theta}{\partial p^H} \to 0$$

That is, recalling that one of the reasons for demanding charging access at workplace is to save cost in case $p^H > p^W$, then an increase in p^H increases the probability of charging at workplace by inducing the employee to increase the share of charging at workplace. On the other hand if $p^H < p^W$, then the employee does not have incentive to switch home charging to workplace, and a marginal increase in p^H doesn't affect the probability of charging at workplace. The implication is that, by manipulating p^H, the electricity supplier can affect the probability of workplace charging related **only** to the amount of charging that employees could shift from home to workplace, i.e., α, ceteris paribus.

Result 1.4: *Charging fee at commercial/public charging stations and the probability of charging at workplace: Obviously, the probability of charging at workplace increases with an increase in charging fee at commercial charging stations, ceteris paribus. That is,*

$$\left(\frac{\partial V^W}{\partial p^C} - \frac{\partial V^H}{\partial p^C}\right) = \lambda D^* (1-d) \geq 0 \Rightarrow \frac{\partial \theta}{\partial p^W} \geq 0 \qquad (1.20)$$

Proof: Partially differentiating equation (1.12) with respect to p^C for i = W, H, we have

$$\frac{\partial V^W}{\partial p^C} = 0$$

$$\frac{\partial V^H}{\partial p^C} = -\lambda^H D^{H,*}(1-\mathrm{d})$$

$$\Rightarrow \frac{\partial V^W}{\partial p^C} - \frac{\partial V^H}{\partial p^C} = \lambda d D^*(1-\mathrm{d})\,|_{V^H = V^W} \geq 0$$

$$\Rightarrow \ \frac{\partial \theta}{\partial p^C} \geq 0$$

The implication is that, by manipulating p^C, the electricity supplier can affect the probability of workplace charging related **only** to the amount of charging that employees charge at workplace instead of at commercial charging stations, not the amount that employees shift from home to workplace, ceteris paribus.

Thus, from results in (1.19) and (1.20), the reader can observe that the electricity supplier that needs to affect the probability of charging at workplace should use both p^C and p^H simultaneously.

Result 1.5*: Workplace charging fee and the probability of charging at workplace: Obviously, the probability of charging at workplace decreases with an increase in charging fee at workplace, ceteris paribus, which can be shown by* applying the envelop theorem on equation (1.12) with the result presented as follows.

$$\left(\frac{\partial V^W}{\partial p^W} - \frac{\partial V^H}{\partial p^W}\right) = -\lambda D^{\mathrm{W},*}\left[(1-d) + \alpha d + d\alpha_2(p^H - p^W)\right] \leq 0 \Rightarrow \frac{\partial \theta}{\partial p^W} \leq 0 \qquad (1.21)$$

Proof: Partially differentiating equation (1.12) with respect to p^W for i = W, H, we have

$$\frac{\partial V^W}{\partial p^W} = -\lambda D^{\mathrm{W},*}\left[(1-d) + \alpha d + d\alpha_2(p^H - p^W)\right]$$

$$\frac{\partial V^H}{\partial p^W} = 0$$

$$\Rightarrow \frac{\partial V^W}{\partial p^W} - \frac{\partial V^H}{\partial p^W} = -\lambda D^{\mathrm{W},*}\left[(1-d) + \alpha d - d\alpha_2(p^H - p^W)\right]_{|V^W = V^H}$$

Note that,

- For $p^H < p^W$, $\dfrac{\partial V^W}{\partial p^W} - \dfrac{\partial V^H}{\partial p^W} \le 0$ since d $\ge$ 0 & $\alpha_2 = \dfrac{\partial \alpha(p^H, p^W)}{\partial p^W} \le 0$

- For $p^H > p^W$, $\dfrac{\partial V^W}{\partial p^W} - \dfrac{\partial V^H}{\partial p^W} \le 0$ since α & $\alpha_2 \to 0$

$$\therefore \frac{\partial V^W}{\partial p^W} - \frac{\partial V^H}{\partial p^W} \le 0 \;\Rightarrow \frac{\partial \theta}{\partial p^W} \le 0$$

The implication is that the employer could control for employees' demand for charging access at workplace by manipulating the charge fee, ceteris paribus.

Result 1.6*: Length of charging time and the probability of charging at workplace: A technological advancement that reduces the time it takes to recharge EVs decreases the probability of charging at workplace, ceteris paribus.*

$$\left(\frac{\partial V^W}{\partial t_c} - \frac{\partial V^H}{\partial t_c}\right) = \lambda^{H*} D^{H*}(1-d)\bar{w}\left(1-\tau\right) \ge 0 \Rightarrow \frac{\partial \theta}{\partial t_c} \ge 0 \tag{1.22}$$

Proof: Partially differentiating equation (1.12) with respect to t_c for i = W, H, we have

$$\frac{\partial V^W}{\partial t_c} = 0$$

$$\frac{\partial V^H}{\partial t_c} = -\lambda^{H,*} D^{H,*}(1-d)\bar{w}\left(1-\tau\right)$$

$$\Rightarrow \frac{\partial V^W}{\partial t_c} - \frac{\partial V^H}{\partial t_c} = \lambda^{H,*} D^{H,*}(1-d)\bar{w}\left(1-\tau\right)_{|V^W = V^H} \ge 0$$

$$\Rightarrow \frac{\partial \theta}{\partial t_c} \le 0$$

Obviously, the lower the time used to recharge the EV at commercial charging stations, the lower will be the probability of charging at workplace, ceteris paribus.

B) When the Employee Pays from Gross Salary

Now suppose that the employee negotiates with the employer to pay from gross salary deduction for charging at workplace, as is the case for many fringe benefits, since this benefits both employees and employers (e.g., De Borger and Wuyts, 2009; Van Ommeren and Wentink, 2012). That is, for their daily charging at workplace, the employee pays from a deduction on gross salary (before tax) so that she and the employer save from tax, obviously, at the expense of government revenue. Accordingly, the budget constraint given in (1.6) becomes, after plugging in c^W given in (1.2) for c^i,

$$x = \left[\underbrace{\bar{w}t_w - \left(\alpha d + 1 - d\right) Dp^W}_{w^W} \right](1-\tau) - \left(1-\alpha\right) dp^H \tag{1.23}$$

where w^W, $w^W \leq \bar{w}$, is the new gross salary of the employee.

Consequently, most of the equations we came across will be affected. Particularly, the effect of p^H on the probability of charging at workplace becomes stronger; the effects of both labor tax and p^W on the probability become weaker; and there is no change on the effects of t_c and p^C on the probability, ceteris paribus. For example, with the same assumption of the employee to pay the reservation fee for charging at workplace, the effect of labor tax on the probability of charging at workplace becomes

$$\left(\frac{\partial V^W}{\partial \tau} - \frac{\partial V^H}{\partial \tau} \right) = \lambda D^* \left[\underset{\substack{\text{Effect of } \tau \text{ on } (i{=}W) \text{ by} \\ \text{increasing the saving from tax}}}{\underbrace{\left(\alpha d + 1 - d\right) p^W}_{>0}} + \underset{\substack{\text{Effect of } \tau \text{ on } (i{=}W) \text{ by reducing} \\ \text{the value of the saved time, } t_c}}{\underbrace{\bar{w}\left(t_w{}^H - t_w{}^W\right)}_{<0}} \right] \tag{1.24}$$

That is, an increase in labor tax increases, on the one hand, increases the probability of charging at workplace by increasing the saving from tax when compared with the case charging fee is paid from income after tax, and, on the other hand, reduces the probability by reducing the value of time that is saved from avoiding the recharging time used at commercial charging station, where the net effect remains ambiguous.

C) *When there is Employer-Paid Charging*

When charging at workplace is provided for free, i.e., when there is employer-paid charging access at workplace, then the budget constraint of the employee becomes

$$x = \bar{w}(1-\tau)t_w - \left(1 - \alpha(p^H, 0)\right) dp^H \tag{1.25}$$

Obviously, the employee has now more money to allot over consumption of x and D, where consumption of D is expected to increases by a higher amount than x due to the substitution effect (i.e., the employee could substitute some of consumption of x by D since the latter becomes relatively cheaper when compared with the price in the absence of free charging at workplace). Moreover, the employee has also more time amounting t_cD (saved by avoiding recharging at commercial charging stations) to allot over consumption of leisure, work and travel, where the time allotted for *D* could be higher due to the substitution effects as well since per unit time consumption for *D* becomes relatively less with accessibility of charging facility at workplace.

2.2. The Employers' Perspective: The Offer of Workplace Charging

2.2.1. Cost for the Employer of Supplying Charging Facility

In this section, we present how the introduction of EV as mode of commuting affects the profit maximization problem of employers (he).

Consider an employer that employs both EV and non-EV commuters. Denote by s the share of EV commuters. He could use the wage rate, levy a per unit electricity fee on electricity used for EV charging or a combination of the two to cover its cost of providing charging facility. By providing charging facility, he incurs cost including installation, maintenance and administrative cost, all denoted by $\bar{c}$, pays a per unit electricity tariff, $\bar{p}$, for the electricity supplier, interest fee, r, for the capital and land used to install the charging facility, and a (possible) per EV user gain, δ from providing charging facility (e.g., tax deduction) in addition to the revenue the he collects from EV users and (possibly) relatively lower wage it pays to EV users who are using the charging facility.

We assume the following relationship:

$$s = s\left(w^{\mathrm{W}}, p^{\mathrm{W}}\right), \text{ where } s_1 = \frac{\partial s}{\partial w^{\mathrm{W}}} \geq 0, s_2 = \frac{\partial s}{\partial p^{\mathrm{W}}} \leq 0 \tag{2.1}$$

That is, the share of EV commuting employees is non-deceasing with the amount of the wage rate, and non-increasing with the amount of charging fee employees pay for using the charging facility. Thus, the choice of the wage-fee combination could have extensive margin effect (i.e., on the number of the charging facility users) on the amount of demand for charging facility.

Similarly, we assume the following relationship concerning the effect of the fee for charging on the amount of electricity demand by each charging facility user (i.e., the intensive margin).

$$d^e = d^e\left(w^{\mathrm{W}}, p^{\mathrm{W}}\right), \text{ where } d_1^{\,e} = \frac{\partial d^e}{\partial w^{\mathrm{W}}} \geq 0, d_2^{\,e} = \frac{\partial d^e}{\partial p^{\mathrm{W}}} \leq 0 \tag{2.2}$$

where d^e is the amount of electricity units the firm expects each user to consume for EV charging, and all other terms are as defined before.

Assuming that there is a wage-fee combination under the participation condition, firms decide on offering the contract (w^{W},p^{W}) by minimizing the per worker cost given by

$$C\left(w^{W}, p^{W}\right) = \bar{w}(1-s) + sw^{W} + \left(\bar{p} - p^{W}\right) d^{e} s + (\mathrm{r}\,\bar{c} - \delta)s \tag{2.3}$$

That is, the employer pays a market wage rate of $\bar{w}$ for employees not using the charging facility, and, for employees using the charging facility, he pays w^{W} incurring the cost associated with provision of the charging facility and collecting revenue from charging fees and from the benefit that arises from charging facility provision, if any. Thus, the employer trades off between proposing, on the one hand, a lower w^{W} and/or a higher p^{W}, which imply a higher cost saving but a lower will also be s and d^{e} in that has to pay $\bar{w}$ for many employees, and, on the other hand, higher w^{W} and/or a lower p^{W}, which imply a lower cost saving.

The first order conditions for the cost minimization with respect to the employer's decision variables, w^{W} and p^{W}, are given as

$$\begin{aligned} \frac{\partial C}{\partial w^{W}} = 0 \;\Leftrightarrow s - \left(\bar{w} - w^{W}\right) s_1 + \left(\bar{p} - p^{W}\right)\left(s d_1^{e} + d^{e} s_1\right) + (r\bar{c} - \delta)s_1 = 0 \\ \frac{\partial C}{\partial p^{W}} = 0 \Leftrightarrow -\left(\bar{w} - w^{W}\right) s_2 + \left(\bar{p} - p^{W}\right)\left(s d_2^{e} + d^{e} s_2\right) + (r\bar{c} - \delta)s_2 - d^{e} s = 0 \end{aligned} \tag{2.4}$$

2.2.2. Result Two

- ***When the employer offers free charging***

Result 2.1. The cost to the employer of EV-commuting employees being offered employer-paid charging access at workplace is given by

$$C\left(\bar{w}, 0\right) = \bar{w} t_w + \underbrace{\bar{p} d^{\max} s^{\max} + (\mathrm{r}\,\bar{c} - \delta) s^{\max}}_{\text{Addition cost due to EV-commuters}} \tag{2.5}$$

where $s^{\max} = s(\bar{w}, 0), d^{\max} = d^{e}(\bar{w}, 0)$. Thus, a significant share of EV as commuting mode could increase labor cost when employers are induced to provide free charging and if δ =0. This could be a concern for firms located at relatively inaccessible areas since they will be induced to provide charging facility to reduce the range anxiety problem of employees which could affect labor supply for these firms if charging facility is not provided.

- ***When $w^{W} = \bar{w}$, but $p^{W} > 0$***

The cost function of the employer when he pays the same wage for EV and non-EV users is given by

$$C\left(p^{W}\right) = \bar{w} + \left(\bar{p} - p^{W}\right) d^{e} s + (\mathrm{r}\,\bar{c} - \delta)s \tag{2.6}$$

The corresponding first and second order conditions for cost minimization are given by

$$\begin{aligned} &FOC_2 : -sd^e + \left(\overline{\mathrm{p}} - \mathrm{p}^{W^*}\right)\left(\mathrm{sd^e}_2 + \mathrm{d^e s}_2\right) + \mathrm{s}_2(\mathrm{r}\overline{\mathrm{c}} - \delta) = 0 \\ &\mathrm{SOC}_2 : -2\left(\mathrm{sd^e}_2 + \mathrm{d^e s}_2\right) + \left(\overline{\mathrm{p}} - \mathrm{p}^{W^*}\right)\left(2\,\mathrm{s}_2\mathrm{d^e}_2 + \mathrm{d^e s}_{22} + \mathrm{sd^e}_{22}\right) + \mathrm{s}_{22}(\mathrm{r}\overline{\mathrm{c}} - \delta) \end{aligned} \tag{2.7}$$

Where p^{W*} is the cost minimizing value of fee given by

$$p^{W*} = \overline{p} + \frac{(r\overline{c} - \delta)\varepsilon_{s_2}}{d^e\left(\varepsilon_{d_2} + \varepsilon_{s_2}\right)} > \overline{p} \text{ for } r\overline{c} > \delta \tag{2.8}$$

where $\varepsilon_{s_2} = \frac{\partial s}{\partial p^W}\frac{1}{s} < 0$ and $\varepsilon_{d_2} = \frac{\partial d}{\partial p^W}\frac{1}{d} < 0$, respectively, are elasticities of the share of employees' demanding charging facility, and the amount of charging employees demand with respect to the fee for charging at workplace.

By applying the implicit function theorem on the first order condition for cost minimization problem after setting $w^W = \overline{w}$, we can observe the effects of the electricity supplier's decision variable, $\overline{p}$, and other parameters on p^{W*} as given by

$$\frac{dp^{W*}}{d\overline{p}} = -\frac{\varepsilon_{d_2} + \varepsilon_{s_2}}{soc_2} > 0, \frac{dp^{W*}}{d\overline{c}} = -\frac{r\varepsilon_{s_2}}{soc_2} > 0, \frac{dp^{W*}}{d\delta} = \frac{\varepsilon_{s_2}}{soc_2} < 0, \tag{2.9}$$

,where soc_2 is the second order condition for cost minimization with respect to p^W. The results given in equation (2.9) intuitively shows that a cost-minimizing employer takes the elasticities of the share of EV commuters demanding charging facility, and of the amount of charge that each EV commuters demands in to account while setting the optimal tariff and when responding to changes in variables associated with provision of charging facility at workplace. For example, if both the number of workers and the amount they charge are less sensitive to the fee they pay for charging, then the employer increases its benefit by increasing at higher amount than the amount electricity supplier increases the electricity tariff on the employer.

2.3. The Electricity Supplier's Perspective: Electricity Load with Workplace Charging

2.3.1. Profit for the Electricity Supplier

The electricity supplier's profit would be affected by workplace charging provision because of the change in demand-supply balance of the electricity power. The degree and sign of the effect of workplace charging on the electricity balance depends on the ex-post balance condition: an improvement in the balance might be observed if there is surplus generation of electricity during daytimes, but a decline in the balance might be found if there is overload of electricity consumption.

To show the effect, let's assume that the electricity supplier divides each day in to three periods based on the electricity demand: the peak period during the day, the evening period and the low-peak night period. Consider a profit function π^e of the electricity supplier for a given day (Yang et al., 2013):

$$\pi^e = \sum_i p_i(q_i)q_i - \sum_i c_0 q_i - \sum_i f(q_i - \overline{q}) \tag{3.1}$$

where i ($i = 1, 2, \dots, T$) is a discrete time of the day, j is a customer type (e.g., households, employers), p_{ij} is the electricity tariff at time i for customer j, q_{ij} is the amount of electricity demanded at time i by consumer type j, c_0 is the marginal cost of supplying a unit of electricity, $f(q_{ij} - \overline{q})$ is the cost due to the variation of demand q_{ij} from the mean consumption $\overline{q}$ during the day. It should be noted that the higher is the variation of demand relative to the daily mean production, the higher is the cost of load congestion. (This implies that additional capacity has to be provided for high-demand periods.).

Consider three time periods during a day according to the demand for electricity and the EV charging time: T^w are the working hours (e.g., 8 am – 5 pm), T^h are the household electricity consumption (e.g., 5 pm – 9 pm and 6 am – 8 am), and T^n are the night hours (e.g., 9 pm – 6 am). The electricity supplier maximizes the profit function π^e subject to the short-run capacity constraint q_i within capacity threshold k ($q_i \leq k$) (the maximum amount of additional capacity that can be supplied in the short term; e.g. without constructing new facilities).

$$p_i^* = \begin{cases} \left[c_0 + f'\left(q_i^*\right)\right] \dfrac{q_i^*}{p_i^*} \dfrac{\varepsilon_i}{(1-\varepsilon_i)} & \text{for } q_i^* \leq q^{\max} \\ \left[c_0 + f'\left(q_i^*\right) + \kappa_0\right] \dfrac{q_i^*}{p_i^*} \dfrac{\varepsilon_i}{(1-\varepsilon_i)} = & \text{for } q_i^* > q^{\max} \end{cases}$$

Remember $p_{T_n} = p^H; p_{T_w} = \overline{p}; p_{T_h} = p^C$

Equation (32) shows that the electricity supplier sets a higher price in the following situations: (i) the customers are price inelastic; (ii) the demand is higher than the mean daily production; (iii) the demand is higher than the capacity of the employer; (iv) the congestion cost is higher, ceteris paribus.

If the electricity demand is highly price inelastic across time, but the overall demand is price elastic, then the monopolist has little influence on shifting demands across day periods in that workplace charging decreases the profit of the supplier due to the congestion cost unless day time electricity production is in excess of consumption. Similarly, if employers are more sensitive to the electricity tariff than households are in that $p^H > \bar{p}$, as is the case in practice for many countries, then workplace charging decreases the profit of the electricity supplier, where the suppler covers the loss in profit partly by increasing the household tariff since households are price inelastic.

3. MODEL FRAMEWORK: THE JOINT PERSPECTIVE

3.2. Production and Consumer Surplus from Workplace Charging Provision

Given the model framework from the three agents' perspectives, it is possible to calculate the consumer surplus of the employee and the producer surplus of the employer from workplace charging provision, as well as the net gain to be shared by the employee and the employer that depends on their bargaining power.

The consumer surplus change, *CS*, for EV commuting employees from accessing the charging facility at the workplace by paying the fee from deduction on gross salary is given by

$$CS = \underbrace{t_w\left(w^{W^*} - \bar{w}\right)(1-\tau)}_{\substack{\leq 0.\text{ Deduction}\\ \text{on wage}}} + \underbrace{\alpha\beta\left(p^H - p^{W*}\right)D}_{\substack{\geq 0.\text{ Saving by}\\ \text{shifting charging from h to W}}} + \underbrace{\gamma(1-\beta)\left(p^C - p^{W*}\right)D}_{\substack{\geq 0.\text{ saving by shifting charging}\\ \text{from commercial charging station to W}}} + \underbrace{\gamma\beta t_c w^{W^*}(1-\tau)\mathrm{D}}_{\substack{\geq 0.\text{ Value of charging time saving}\\ \text{by charging at W instead of at com.}}} \tag{3.2}$$

On the other hand, the production surplus, *PS,* for the employers from provision of charging access for an employee is given by

$$\mathrm{PS} = \left(\bar{w} - w^*\right) + \delta - r\bar{c} - \left(\bar{p} - p^W\right)d^e \tag{3.3}$$

It should be noted that some of the gains for employers are transferred from employees, and vice versa. The net gain for both employees and employers to share, *CPs,* is the sum of the consumer surplus and the production surplus.

$$\begin{aligned} CPs &= CS + PS \\ &= \underbrace{\tau(\bar{w}\text{-}\mathrm{w}^{W^*})}_{A_1} + \underbrace{\alpha\beta\left(p^H - \bar{p}\right)D}_{A_2} + \underbrace{\gamma(1-\beta)\left(p^C - \bar{p}\right)D}_{A_3} + \underbrace{\gamma t_C D(1-\beta)\bar{w}(1-\tau)}_{A_4} + \underset{A_5}{\delta} - \underset{A_6}{r\bar{c}} \end{aligned} \tag{3.4}$$

The following terms compose the gain: A_1 is the tax saving, which has a non-negative value, that is incentive for both employer and employee to negotiate about the workplace charging being paid from gross salary at the expense of government revenue; A_2 is the cost saving for shifting charging from home to work, which has a non-negative value for $p^H > \bar{p}$ and zero; A_3 is the cost saving (incurred) by shifting charging from commercial charging stations to workplace, which has a non-negative value for $p^C > \bar{p}$; A_4

is the value of time saving for the employee charging at the workplace rather than at commercial stations; A_5 is any gain from offering the workplace charging facility, e.g., government subsidy; and A_6 is the fixed cost of installing and maintaining the charging facility including land rent.

The effect of government policies and other decision variables is calculated by differentiating the *CPs* with respective to the variables and parameters given in equation (3.4).

3.2. The Three Agents Combined: Employees, Employers and Electricity Supplier

A remaining question is whether there is an incentive for the three agents to bargain concerning workplace charging provision. Assuming that the profit of the supplier is maximized before the introduction of workplace charging, the model framework has shown that workplace charging decreases the profit of the supplier unless there is a surplus production of electricity during working hours when compared with other periods of the day. Thus, unlike the employee and the employer who have incentives to have workplace charging, the electricity supplier has disincentive for workplace charging provision since its preference is for EVs to be charged during off-peak periods of electricity consumption.

This highlights the conflict of interest between employee and employer on the one hand, and the electricity supplier on the other hand. For this reason, the supplier could engage in various mechanisms to deter workplace charging provision.

Firstly, the supplier could discourage workplace charging by offering attractive tariffs for nighttime charging, particularly when the employees' nighttime demand for electricity is highly elastic. In the case that the nighttime demand for electricity is price inelastic, the supplier may not be able to discourage workplace charging. Secondly, the supplier prohibits arbitrage by having legal support to stop employers from "selling" electricity because the employer has a profit from offering the charging. However, this may not hold water because it could be administratively costly for the supplier to control whether each employer is using the charging facility at workplace for profit-maxing from arbitrage.

The supplier has a handful of constraints to discourage workplace charging. Firstly, the provision of a charging facility is a gradual process that the supplier may not be aware of and, once the employer installs the facility, it is not easy to stop the process since the installation cost is expensive and since the profit of the employer would be affected. Secondly, accessibility to a workplace charging facility could have a handful of benefits to employees and employers that could be costly for the supplier to use a price instrument to discourage workplace charging.

Accordingly, the workplace charging provision is a form of a sequential game that the last mover (i.e., the electricity supplier) has little to influence. Period 1: the electricity provides sets the tariffs. Period 2: the employer decides whether to offer charging and with which contract. Period 3: the employee decides whether to accept the contract (extensive margin) and how much to charge at the workplace. The electricity supplier changes the electricity tariff, but this tariff may not be effective to correct the distortion due to workplace charging since (i) the tariff will be shared by all customers, (ii) electricity demand is usually price inelastic, and (iii) the electricity tariff for industries (employers) is usually higher than for households due to price elasticity and average cost of supplying electricity.

3.3. The Impact of Workplace Charging Provision on Social Welfare

Having observed that there is a benefit for both employees and employers to share from negotiating over workplace charging facility, at least in countries where the electricity tariff for employers is lower than for households, which is the case for most of the countries (IEA, 2012), and having considered that the electricity supplier may have little control over workplace charging, we present analytical illustration of some of the effects of workplace charging accessibility on social welfare.

The transport literature predicts that travel demand increases with decreasing travel cost. Thus, a cheaper than home charging fee at workplace, because of either wage negotiation between the employer and the worker, lower electricity tariff for employers than for households, and/or of productivity reason, could increase travel demand by EV commuters, adversely affecting road traffic and car sharing, and increasing the demand for electricity (by EV commuters). Moreover, availability of cheap charging at workplace could induce other employees to switch travel mode to EV, which may not be socially desirable if the switch is from non-conventional car (e.g., bicycle, public transport) to EV.

The second negative externality of workplace charging is the congestion effect on electricity load transmission. We discussed before that EV commuters would transfer (αd) amount home charging to workplace if EV charging fee at the workplace is cheaper than the fee at home charging. This increases the electricity congestion problem (peak-load problem) since electricity consumption is usually high during daytime. This could induce the electricity supplier to increase the tariff, which, in turn, could affect the welfare of the general population including new electricity-intensive investments.

The number of EV charging stations could be more than the socially optimal number since each EV-commuter who agrees to have charging access at the workplace will receive a charging station that also serves as a parking place for the whole working hours of the day. The ideal number of charging stations is that there is no queue for charging and that there is no vacant charging station. This is unlikely in the case of charging stations at the workplace since it may not be convenient for workers to interrupt work to switch charged and to-be-charged EVs at the middle of the working hours, implying that each EV users who agrees with the employer will have charging facility, resulting underutilization of the charging facility.

Another effect of workplace charging is when workers and employers negotiation over wage rate in return for free workplace charging at the expense of government revenue from labor tax amounting, inducing the government to increase (distortionary) tax on other government revenue sources. The government´s revenue from electricity consumption tax could also be lower since aggregate demand for electricity could decline following a tariff increase by the supplier to cover the congestion cost that arises from workplace charging.

3.4. The Role of the Government for Social Optima

We have seen before that labor tax will not be effective in curtaining negative externalities since increasing the labor tax increases the incentive of increasing tax exempted fringe benefits including workplace charging while reducing tax decreases government revenue that is used to provide public goods. One of the policies that will increase welfare, at least when EVs constitute a significant share of passenger fleets, is to impose road tax that is non-decreasing with the quantity of distance travelled so that to reduce the externality of higher car usage that arises from cheap charging fee at workplace.

Prohibiting employers from providing free charging access at the workplace combined with a very cheap tariff for nighttime electricity consumption improves welfare.

Setting time-of-use pricing in that the electricity tariff will be higher during daytime, which could discourage employees to shift home charging to workplace makes provision of charging facility costly for employers. However, this may adversely affect investment. Moreover, the electricity supplier may not have power, under competitive market, to use time-of-use pricing that imposes higher tariff on industries since industries could also have a higher bargaining power.

4. CONCLUSIONS

This paper has considered EV-commuting employees demand for workplace charging, the incentives for the employers to provide charging facility at workplace, and the consequences that arise from accessibility of workplace charging. Once workplace charging accessibility is started either by government initiatives to boost the share of EVs or by companies to increase productivity, EV-commuting employees prefer to work for companies with charging facility access, triggering other employers to provide too. From employees perspective, we found that risk aversion behavior towards driving range anxiety problem coupled with the value of time associated with longer recharging time at commercial/public charging stations increases the demand for workplace charging both at extensive (i.e., by new EV users) and intensive (by existing EV users) margin. Moreover, we found that employees´ reservation fee for EV charging at workplace is higher than their reservation for charging at commercial charging stations, where the magnitude of the reservation fee difference depending on the value of time and on the length of time it takes to recharge the EV at commercial charging stations.

The benefit for employers and workers to share from availability of workplace charging is higher when: i) they agree to pay for workplace charging on gross salary and when the labor tax is high; ii) employers pay less electricity tariff than households do; iii) recharging the batteries of EVs takes longer time.

Accessibility of cheaper charging facility at workplace, while saves the charging time and increases the share of EV-commuting at the expense of fewer non-EV commuting modes, it results in unintended results including electricity peak-load problem, decreases the consumers surplus from consumption of electricity for household use, and increases car use that worsens the traffic congestion problem and that increases electricity consumption for EV charging. For the electricity supplier, workplace charging increases the cost of supplying electricity by aggravating the daytime peak-load problem and by increasing the demand variation from the mean that induces the supplier to expand capacity and to increase the tariff. Tax based on yearly travel distance, charging quota limit on workplace charging, and restriction on free workplace charging access improves social welfare.

The results from this study are relevant in (i) helping to predict the choice of time and place of charging of EV commuting employees and its effect on electricity demand, (ii) supporting employers to understand the implications of workplace charging provision, and (iii) providing electricity suppliers with information for correct electricity demand predictions.

While presenting untended consequences from accessibility of workplace charging and proposing policy options to curtain these results, the paper assumes that, the main charging takes place during nighttime at home in the absence of workplace charging facility. If the latter is not the case (i.e., if EVs are charged during peak household consumptions of elasticity), and if the electricity consumption peak-load problem is higher during household electricity use than during industry use, then accessibility of workplace charging reduces the electricity peak-load problem, at least in the short-run, and hence, the only unintended consequence of workplace charging will be an increase in car use and the resulting externalities in the case when fee for EV charging is cheaper at workplace than at home for employees.

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