

Optimal Charging of EVs in a Real Time Pricing Electricity Market

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ABSTRACT

The idea of grid friendly charging is to use electricity from the grid to charge batteries when electricity is available in surplus and cheap. There are several ways of achieving this, for example using droop control, using night time electricity tariffs, or using smart metering. The goal is twofold: to avoid putting additional load on the electricity grid and power generation, and to reduce the cost to the consumer.

This paper looks at the saving potential when charging an electric car using real time tariffs provided by a smart meter, using the Ameren tariffs in Illinois as an example. If prices are known in advance (day-ahead pricing), the optimization only requires picking the cheapest time slots for charging the battery. Further savings can be made by using real time prices that are not known in advance, but the optimization problem then depends on price prediction models, and it becomes much more difficult to solve. This paper presents a simple suboptimal approach, and it quantifies the potential improvements that could be made using more sophisticated price predictions.

The result is that cost savings in the order of about 50 USD (1/3 of the electricity costs) are feasible if a fast charger is used using real time pricing. The scale of the savings is such that complex optimization strategies are not worthwhile, and for the foreseeable future simple solutions are expected to be more cost effective.

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INTRODUCTION

The power and transport sectors are the first and second largest sources of global greenhouse gas (GHG) emissions. The transport sector contributes to both emissions and energy use are growing quickly by the year and World Energy Outlook projections predict that they will overtake the power sector by 2035 [1][2]. In 2007, the road transport sector accounted for 71% of the total emissions attributed to the sector as a whole, with 63% of them generated by passenger cars [3]. The world community has set ambitious targets for GHG reduction in the future and many countries (especially the developed nations) have registered emission reduction targets or commitments to the actions by 2020. As an example, the European Union's (EU) ambitious target is set for 2020 to reduce GHG emissions by at least 20%, improve energy efficiency by 20% and ensure the contribution of renewable energy sources in gross energy consumption is 20% [4].

Electric Vehicles

The problem of climate change has been demanding cleaner and more energy-efficient powertrains, for over two

decades. However, the recent route towards 'greener environment' policies has brought electric vehicles (EV) to attention and EV research to the forefront of many original equipment manufacturers' (OEM) future plans.

1. Hybrid electric vehicles (HEV) are a combination of the typical internal combustion engine (ICE) and a battery electric vehicle (BEV), with the electric motor supplying auxiliary power when the ICE is not in use. The ICE is able to recharge the batteries when the EV is not in use and the on board computer manages the correct mix of electric and fuel power depending on the engine and battery power available. The ICE essentially works as a range extender while the urban battery use reduces overall emissions.

2. BEVs are purely battery powered and use a motor or combination of motors to drive the vehicle. BEVs suffer from limited driving range because of battery limits. However, research in battery technology is rigorous in the current environment and is bringing many improvements in range and battery life. Currently, lithium-ion (Li-ion) batteries are the most promising battery technology with the ability to store significantly more electricity in much lighter cell packs.



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3. Plug-in hybrid vehicles (PHEV) combine the advantages of the HEV and BEV. They work in two modes: fully electric or hybrid. The ICE can facilitate the drive or function individually, just like the BEV. The other advantage this technology has is that it can be charged using a wall socket just like BEVs thus being able to have electric power for most urban trips without engaging the ICE at all. Currently, the pure electric drive mileage of PHEVs is limited to 10 and 60 miles depending on battery size.

HEV have been mildly successful in the past decade with the major producer, Toyota (Prius) selling 2 million units by 2009. Whilst it is widely accepted that market forces alone have not been able to make the EV a first choice for many consumers; government policy support, research to make EVs less expensive and economy improvement will improve their market significantly [5][6]. The barriers in EV penetration into the main market have been limited driving range and high cost of electric technology. Although, electric driving ranges are limited for all three HEV, PHEV and BEVs; surveys have indicated that 47-55% of single vehicle usage in a single day is less than 20 miles, with 82-88% of vehicles travelling less than 60 miles [7]. Kang and Recker's 2009 [7] study concludes that it is possible to convert between 80% to 90% of daily mileage to electric when using PHEV with a 60 mile range in California; under the condition that both home and public place charging stations are in use. These numbers indicate that EVs are more feasible than previously thought. JP Morgan performed a study in 2009 which forecasted 11.28 million EVs worldwide by 2020 and 20% of the total cars sold in North America [8].

Impact of Electric Vehicle Penetration

Although, a change from ICEVs to EVs means a little change for consumers in context of refueling patterns; their main impact will be that on the already stressed electric grids. The batteries of these vehicles require long times and high power and currents for charging. For most domestic users, charging will take place overnight at their homes. Moreover, the tendency to plug the vehicle in as soon as they reach home is high. Other typical charging loads could be concentrated in office or public car parks depending on the actual use of the vehicle during the day. If the consumers charge the vehicles after every trip: for example, every time they reach office or a supermarket or come home and leave again, this would be of even higher concern to electricity peaks. Although, peak load times would be different in different parts of the world, depending on weather, some kind of load shifting to accommodate EV charging may be required.

The subsequent effect to consider is the logical change to electricity generation and retail or wholesale prices in the future. The higher peaks, consumption and addition of more renewable energy might change the prices in markets significantly. In most countries the industrial sectors are on wholesale electricity prices- buying electricity at lower rates

during off-peak hours. There is a possibility for such 'spot-markets' even for domestic electricity consumers as is case in Portugal, Germany, some parts of continental Europe and a few states in the USA. In such markets, the consumers are encouraged to shift their electricity usage to off-peak hours through high-price updates/alerts either hourly or daily. Advances in 'Smart-Grid' technology can allow this elastic behavior from households, helping them to reduce costs. The meter records hourly consumption and also alerts the consumers of the latest and future prices. This essentially ties in with the idea of 'Real-Time Pricing (RTP)' where prices change on an hourly basis as mentioned before. The smart-grid technology includes communication devices which allow real time consumption checking and communication to and from the consumers' meter. The smart grid is being promoted and provided to consumers in the U.S.A. for some time now. Electric utility providers in California, Colorado, Florida, Illinois, Indiana, Ohio, Texas, Washington and some other states have already been introducing smart grids to many customers. There is also a strong financial incentive being provided for both smart grid research and introduction via the Energy Independence Act of 2007 and the US Stimulus Package of 2009 [9]. This strongly indicates that smart grids and RTP are the future of electric pricing and management. The state of Illinois is a good example where RTP has been available to customers since 2003. The RTP programs have been successful in reducing the participating consumers' electric usage and bills and shifting usage to non-peak times of the day [10]. The two electricity providers which allow the choice of RTP are Amaren and ComEd. Amaren's Power Smart Pricing (PSP) and ComEd's Residential Real Time Pricing (RRTP) programs have reduced their peak demand in the range of 15% and achieved participant bill savings between 10-15% [10].

The above discussion shows that there are two problems to consider when EV penetration becomes high in the future. Firstly, it will be important to manage the electricity loads and peak demands due to user profile of EV charging. Some load may have to be shifted from peak afternoon and evening times in some manner either by persuading or enforcing the consumer to charge earlier or later. Secondly, charging the vehicle without control might also be a disadvantage for the consumer due to the possibility of a future with RTP for electricity. However both these problems can be looked as an opportunity for EVs. The flexibility of charging time can be looked as an advantage for load shifting opportunities and the daily mileage being enough for urban travel means times of charging can be varied. When smart-grid infrastructure is in place in the future, communication with it can not only allow automatic flexible charging but can also be used to provide electricity from the vehicle to grid (V2G). V2G technology can level any load fluctuations by supporting the grid and gives the opportunity to sell surplus electricity in the EV to national grids). Flexible charging by smart-grid communication can allow future EVs to access RTP for electricity and charge for the lowest cost.

Finally, the charging of electric vehicles has impact on the electricity grid on a number of time scales, ranging from the millisecond range to hours and days. The potential is there for all these effects to be beneficial to the grid: active inverters can absorb harmonics, they can apply droop control to enhance grid stability, and they can pick times for charging when excess electricity is available. However, very little progress has been made towards these goals so far, and regulations often only aim to prevent harmful effects, not to leverage potential benefits. This paper concentrates on the slow time scale, and what kind of effects smart metering has on the optimal charging timing.

Table 1. Grid Effects by Timescale

Time Scale	Significance	Function	Advantage
Very Fast 0.1-10ms	Harmonics and Noise	Absorbs Disturbances	Improves Local Power Quality
Medium 0.1-10s	Grid Frequency Stability	Droop Control	Supports Grid
Long 0.1-10h	Battery Charge and Electricity Prices	Cost Optimisation	Reduces Charge Cost

LITERATURE REVIEW

Studies on the effect of EV penetration to the electricity grid date back to the 1980s. In [11], Heydt discusses the effects on and of electric load management due to EV penetration. The study concludes that it is likely that charging will occur at peak demand times and some form of load management must be introduced to manage the additional EV charging load. Webster's review of electric infrastructure in the UK [12] concludes that in case of high EV penetration, it is likely that battery recharging times will coincide with peak electricity demand. Measures must be taken to avoid this although the electric networks can cope with the additional load. Both these authors consider the user profiles to be of primary impact on recharging times. In a much more recent study, Camus et al. [13] simulate a 2020 scenario of 2 million EVs in the Portuguese spot electricity market, considering different mixes of renewable power generation. They conclude that with low renewables and high cost, charging of EVs during peak times can lead to electricity prices of 17 Euro cents/KWh. This can be brought down to 7 Euro cents/KWh with off-peak charging and with higher renewables and low general costs, down to 5.6 Euro cents/KWh. Mahalik et al. [14] performed a simulation to realize EV impacts on the Illinois grid in 2020 and concluded that on-peak uncontrolled charging would require an additional 400 MW unit to support the state's reserve margin. If off-peak and controlled charging is facilitated, no additional supporting grid would be needed. The additional electricity required could be provided by reducing the electricity exports

Illinois makes. All the above research recognizes the problems related to on-peak charging in a high EV penetration scenario but no mathematical formulations are presented for optimal charging.

Acha et al. [15] present a time coordinated optimal power flow (TCOPF) tool for distribution networks to decide on load control approaches for EVs in the future. The algorithms concentrate on showing different charging strategies to the electricity providers to see how they may have to change energy production to reduce carbon emissions and cost. They conclude for the UK context that, UK will need to introduce more renewables or non-carbon fuel mix to offset costs and emissions for high EV charging scenarios. Kristoffersen et al. [16] use a linear regression to minimize charging costs based on the Danish (Norpoo) electricity market prices. The study made the assumption of an EV fleet controller who managed the participation of EVs during charging or providing electricity to the grid, based on fleet driving patterns and electricity prices. They concluded that EV driving patterns and hence charging time is highly flexible during the day but not from day to day. In [17], Rotering and Ilıc present two time-discrete algorithms for optimal charging; one considering only minimizing cost and the other also taking into account V2G support. They perform a case study based on the California day ahead electricity price market and conclude that optimal/smart charge reduces the charging cost from 0.43 USD to 0.2 USD daily. In case of V2G support, the profit amounts to 1.71 USD including charging.

The following paper presents a study on an optimal charging algorithm for future EVs which considers battery charging in a spot or real-time electricity market. The idea is to automatically manage the charging time once the vehicle is plugged in to provide a full charge when required but at the lowest cost. This means that the charging would be shifted to off-peak hours when the price is lower. The subsequent advantage of this can be to the grid in a way of load shifting. Firstly the optimal charging problem is explored based on time-discrete solution and then variability is introduced with the assumption that there might be power reduction at peak times. Secondly, the implication of introducing dynamics in the optimal solution achieved is looked at in the context of the unpredictability of the actual electric prices. A stochastic approach is discussed for the solution of the dynamic problem. Lastly, the example of Illinois RTP is taken and a possible scenario and case study for optimal charging is shown.

THE BASIC OPTIMAL CHARGING PROBLEM

A highly abstracted version of the optimal charging problem will be introduced first because this leads to a very simple solution that lends itself well to both implementation and further analysis. Additional details will be added and discussed afterwards.

The basic optimal charging problem is defined in discrete time with step size. It has one control variable: the charging power p_k . The power is subject to two constraints: it cannot be negative and there is a constant maximum power $\bar{p}$ such that $p_k \in [0, \bar{p}]$.

The behavior of the system is determined by two separate dynamics: the battery state and the total cost. Both accumulate (integrate) over time and the only difference is the coefficient.

The battery state E_k is an integral of the charge power over time:

$$E_{k+1} = E_k + Tp_k, \quad (1)$$

assuming that the self-discharge and charging losses are negligible.

The total cost C_k is also an integral of the charge power but weighted by the current electricity price:

$$C_{k+1} = C_k + Tc_k p_k, \quad (2)$$

where c_k denotes the electricity price and $C_0 = 0$. The price is a disturbance for the system, for now it is assumed that it is known in advance, which simplifies the problem significantly.

The total number of steps l to consider with $k = 0 \dots l$ is also defined in advance.

Definition 1: The basic optimal charging problem.

The basic optimal charging problem is defined by the cost function $J = C_l$ representing the total electricity cost and the boundary condition $E_l = E_{full}$, which requires the battery to be fully charged at the end of the charging process.

Because no discharge is allowed, it is not necessary to impose limits on the charge state E_k , as it is already bounded by E_0 and E_{full} .

The advantage of using this simple model is that the final state and cost can easily be calculated as:

$$E_l = E_0 + \sum_{k=0 \dots l-1} Tp_k \quad (3a)$$

$$C_l = \sum_{k=0 \dots l-1} Tc_k p_k \quad (3b)$$

Lemma:

The solution to basic optimal charging problem is

$$p_k^* = \begin{cases} 0, & c_k > c' \\ p', & c_k = c' \\ \bar{p}, & c_k < c' \end{cases} \quad (4)$$

The threshold price c' is one of the prices c_k and the threshold charging power p' can be found from the boundary

condition using a linear equation. There may be more than one solution if several time steps have the same price $c_k = c'$, and for now it is assumed that is not the case.

Proof:

The proof has two parts. The first step is to demonstrate that the presented from is an admissible solution to the problem and the second is to show that it is indeed the/an optimal solution.

With the given control law, the final charge state E_l is a function the initial state E_0 , the threshold charging power p' and the number of full charging cycles n that satisfy $c_k < c'$.

As long as $E_l \geq E_0$ and $E_l \leq E_0 + lT\bar{p}$, the problem has a solution.

Assuming that the prices are different at each time step, there is exactly one solution, which is given by the following two equations:

$$n = \text{floor} \frac{E_l - E_0}{T\bar{p}} \quad (5a)$$

$$p' = \frac{E_l - E_0}{T} - n\bar{p} \quad (5b)$$

This solution is not just admissible but also optimal because any deviation from this solution within the charging power limits leads to a higher cost. In order to maintain the same final charge state c_l , an alternate solution needs to be decreased the charging power at some time step $p_i = p_i^* - \Delta p$, and increased it at another $p_j = p_j^* + \Delta p$. This maintains the same integral and therefore satisfies the boundary condition. But increases are only admissible when $p_j < \bar{p}$, and decreases only when $p_i > 0$. It follows that $c_i \leq c' \leq c_j$, and therefore the net effect is an increase of charging cost by $\Delta J = T(c_j - c_i)\Delta p$. (qed)

VARIATIONS OF THE BASIC CHARGING PROBLEM

There are several extensions that can be made to make this problem more applicable. This section will list a number of variations that lead to essentially similar solutions. The basic approach is that the variation is converted back into the original form of the problem, so the same simple solution algorithm can be used.

Varying Charge Power Limit

The amount of available charging power $\bar{p}$ may change over time, for example to do electricity use restrictions at peak load periods. This means a new time series $\bar{p}_k$ has to be introduced. The closed formulation of the optimal solution is no longer applicable but a simple iterative algorithm can still find the best solution. The proof applies appropriately.