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Real-time renewable energy incentive system for electric vehicles using prioritization and cryptocurrency

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HIGHLIGHTS

- A incentive system design incorporating the concepts of prioritization and cryptocurrency for electric vehicle users.
- Blockchain cryptocurrency provides additional incentive to users and cost savings to aggregators.
- Implementable and scalable ranking algorithms.
- Optimal strategy for incentivized users to maximize overall renewable usage.
- Numerical simulation and experimental data analysis of 15 months to verify the effective of incentives.

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ABSTRACT

Significant increase in the installation and penetration of Renewable Energy Resources (RES) has raised intermittency and variability issues in the electric power grid. Solutions based on fast-response energy storage can be costly, especially when dealing with higher renewable energy penetration rate. The rising popularity of electric vehicles (EVs) also brings challenges to the system planning, dispatching and operation. Due to the random dynamic nature of electric vehicle charging and routing, electric vehicle load can be challenging to the power distribution operators and utilities. The bright side is that the load of EV charging is shiftable and can be leveraged to reduce the variability of renewable energy by consuming it locally. In this paper, we proposed a real-time system that incorporates the concepts of prioritization and cryptocurrency, named SMERCOIN, to incentivize electric vehicle users to collectively charge with a renewable energy-friendly schedule. The system implements a ranking scheme by giving charging priority to users with a better renewable energy usage history. By incorporating a blockchain-based cryptocurrency component, the system can incentivize user with monetary and non-monetary means in a flat-rate system. The effectiveness of the system mechanism has been verified by both numerical simulations and experiments. The system experiment has been implemented on campus of the University of California, Los Angeles (UCLA) for 15 months and the results show that the usage of solar energy has increased significantly.

1. Introduction

The rising awareness of global warming and energy sustainability has led to a worldwide effort to introduce more Renewable Energy Resources (RES) into the current energy mix. Currently, the most promising and popular RES include Photovoltaics (PV), wind and geothermal [1–3]. However, due to their variability and intermittency issues, it's not a trivial task to integrate these RES into the electric grid. For example, PV energy has created a significant increase in daytime generation and a valley of net demand in the afternoon, followed by another net demand peak at night, most famously described by California "duck curve" [4]. Wind energy suffers from problems such as generation curtailment due to transmission and demand issues all over the world [1]. Extensive work has been done to address the RES integration issues in microgrid [5–8]. Dawound [5] reviewed common optimization techniques for microgrid with RES. Mehdizadeh [6], Javidsharif [7] and Lorenzo [8] propose scheduling of renewable-based microgrid using information gap decision theory, multi-objective optimization and model predictive control.

At the same time, the ownership of electric vehicles (EVs) has been rapidly growing all over the world. In United States, the projected sale of EVs is expected to reach 2.3 million, or 19% of the total sales by 2050

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Nomenclature

$\overline{k^i}$	user i profile features other than solar score
$\overline{R}$, $\overline{P}$, $\overline{D}$	set of user starting time, stop time and energy demand
$\overline{s}$, $\overline{K}$, $\overline{a}$	set of solar score, user feature and power provided
γ	rate of issuing SMERCOIN for each aggregator per kW h of RES consumption
$\mathbf{a}$, $\mathbf{a_i}$	charging strategy for charging box and user i
$\mathbf{B_i}$	set of parameters set up by users with higher priority than user i, indicating the SMERCOIN compensation per minute for boosting
$\mathbf{F}$, $\mathbf{F_i}$	feasible set for charging box and user
$\mathbf{I}_t$, $\mathbf{I}_{h,t}$, $\mathbf{I}_{l,t}$	set of users, higher priority users and lower priority users in a charging box at time t
$\mathbf{T_i}$, $\mathbf{T_i'}$	open time slots for user i from server and combined with user's own open time plan
$\mathscr{D}(v, y)$, $\mathscr{S}(v, y)$	demand and supply as function of price and utility value
$\mathscr{D}$, $\mathscr{S}$	demand and supply of SMERCOIN in the user-level exchange
$\mathscr{T}_i$, j	set of available slots for user i for multi-boxes, chosen box index
ρ, λ_i	the scaling factors for user level optimization
$\widetilde{\mathbf{D}}$	the system estimated user demand
$\widetilde{E}$, $\overline{E}$	energy allowance per cycle and the set of energy tracker in Priority Round Robin
$a_{\max}$	maximum rate a charging box can provide (hardware configuration)
$a_{i,t}$, $a_{i,t}^p$	power consumption of user i at time t and that in priority charging system
$a_{p,t,\text{raw}}$	raw data reading from RES generation meter at time t
$a_{p,t}$, $a_{s,t}$, $a_{v,t}$	RES generation, power of charging box, power of charging station v at time t
b	base aggregator conversion rate from SMERCOIN to fiat money
c_i	total SMERCOIN price for boosting for user i
g_i	time delayed for providing boosting to user i
$l_i(r_{io}, p_{io}, d_{io})$	loss function of user i considering change of original plan
R_i, P_i, D_i	starting time, stop time and energy demand of user i
R_i^f, P_i^f, D_i^f	starting time, stop time and energy received of user i in fair sharing system
r_{io}, p_{io}, d_{io}	user's original request parameters
s_i	solar score of user i
$t_{n,s}$, $t_{n,e}$	start and end time of n-th session
u	overall RES consumption rate by EV
u_c	solar consumption ratio
$u_{i,n}$	RES consumption for the n-th session of user i
v, e, y	total, additional exchange and utility values of SMERCOIN
$w(s_i, \overline{k^i})$	weight function to calculate user priority

[9]. This creates an increase in electric energy demand and puts additional stress on the power grid. The problem will be further amplified with more powerful Direct Current Fast Chargers (DCFC) and vehicles with larger batteries. Uncontrolled EV charging creates large load variations in the local distribution grid, amplifying the peak further and reducing system reliability and power quality [10–12]. To understand how EV charging will impact the power distribution grid, Mozafar [13] studies the effects of EVs on power system demand, stability and reliability. Kheradmand [14] evaluates the distribution grid's well-being and reliability in the presence of EVs. Amini [15] proposes a two-stage approach to allocate EV charging lots and RES in the distribution network. Mohammadi [16] presents a decentralized decision-making algorithm for collaborative optimal power flow in the transmission and distribution networks. Nienhueser [17] and Schuller [18] discuss the impact and future of RES integration with EVs considering EVs' economic and environmental impacts and load flexibility.

With coordination and scheduling, however, EVs could be a valuable asset as a shiftable demand in the grid to alleviate over-generation and night peak problems [19]. Modern EVs have the ability to serve as a temporary controllable load and an aggregation of EVs can be a powerful tool to adjust the load variation on the electric grid without major impact on individual users. If the coordination of an EV aggregation is coupled with the dynamics of RES generation, the effect of EVs' load on the external grid can be minimized while offsetting the negative impact of RES on the grid. There exists literature on how to guide electricity users' behaviors using incentives, demand response [20–25] and smart charging algorithms for aggregated EVs [26–28]. Valles [20], Eissa [22] and Yu [23] model incentive programs considering user responsiveness, multiple resources' coordination and hierarchical electricity markets. Zhang [21], Haghi [24] and Zhao [25] provide market investigation, benefit analysis and execution experience of providing incentives. Rubino [26], Mortaz [27] and Lu [28] review and propose microgrid scheduling and dispatch algorithms with EV smart charging. Most of the current literature discusses traditional monetary incentive and few incentive programs on electric vehicles' consumption behavior exist in current market.

Many works of literature have investigated approaches to increase the utilization of RES with smart EV charging. Mouli [29] designed a solar harvesting system used to charge EVs. Researchers [30–33] consider EVs as a part of larger loads, such as households or buildings, supported by a wide variety of RES and use linear programming [30], convex programming [31], mixed-integer programming [32] and semi-Markov decision process (SMDP) [33] to find the optimal strategies to maximize RES utilization. Most of the technologies of RES maximization either involve Vehicle-to-Grid (V2G) capability or placement of energy storage. However, large energy storage is still expensive and the V2G technology is also far from being standardized and popularized. In fact, there are few EVs with V2G capability on the road today.

Smart charging algorithm designs with various optimization approaches are also widely proposed [34–37]. Several real-time smart charging algorithms are also proposed based on use priorities [38–40]. Many minimize energy costs for drivers and aggregators assuming a dynamic or Time-of-Use (TOU) pricing scheme. While this is an effective approach, flat-rate pricing is still dominant in the real world and there are many obstacles for full implementation of dynamic pricing. If no dynamic pricing or monetary incentive is imposed, the performance improvement of cost reduction would be limited. Moreover, most of the studies assume complete information on user behavior and full control of each EV. This, however, is hardly the case in actual implementation. Experiments and implementation experiences of optimal energy management are reported [41–44]. Peng [41] and Lopez [42] provide deployment experience of renewable microgrid in Singapore and Andean countries. Quashie [43] and Arcos [44] verify the effectiveness of their proposed control algorithms through experiments conducted in Canada and Spain. Zhang [45] reports an operating Energy Management System (EMS) and proposes a flat-rate real-time smart charging algorithm assigning priority based on users' charging profile and demand. These reported systems are mostly multi-resource Demand Side Management systems without particular focus on EV and RES integration in microgrid.

The emerging technology, blockchain [46], shows an opportunity to provide incentives to users without going through the traditional pricing scheme posed by utility or aggregators. Blockchain provides decentralized and mutually trusted cryptocurrency transaction system for