Online Supplement
"Crowdsourcing Electric Vehicles for Omni-Sharing Distributed Energy Storage"

Appendix A: Mobile Storage Sharing

A.1. Uniform Price

Additional Discussion on the Range of the Uniform Price and Assumption 2. The range of the uniform price λ ensures that the integration limits in Equation (5) are always valid, i.e., the upper limit $\hat{r}_m(\overline{e}-\underline{e},\lambda)>0$ and the lower limit $\hat{e}_m(r,\lambda)>0$ for any $m\in\{R,P\}$. We derive this price range through the following three steps.

(1) Expression and property of the discharge-down-to energy level $\hat{e}_m(r,\lambda)$.

Recall from Section 4.2 that the CSEV drivers' surplus maximizing condition occurs when the marginal adequate payment decreases to equal the marginal revenue earned by the driver, that is, $\partial\Lambda_m(\hat{e},r)/\partial\hat{e}+\mu=\lambda l(r)$, where the non-negative Lagrange multiplier $\mu\geq 0$ satisfies $\mu\hat{e}=0$ and $l(r)=\eta_d(1-\eta_l r)$ represents the energy sharing efficiency. To find the discharge-down-to level $\hat{e}_m(r,\lambda)$, we solve the first-order condition for CSEV drivers' surplus maximization:

$$\hat{e}_m(r,\lambda)=-\frac{1}{\omega_m}\ln\frac{\eta_d(1-\eta_l r)\lambda-\lambda_L/\eta_c-\varrho r-g(\delta-1)}{\pi_m\omega_m},\quad \forall m\in\{R,P\}.$$

Taking $\hat{e}_m(r,\lambda)$ as positive implies $\eta_d(1-\eta_l r)\lambda-\lambda_L/\eta_c-\varrho r-g(\delta-1)>0$. By taking the partial derivative with respect to r and λ, i.e., $\partial\hat{e}_m(r,\lambda)/\partial r=\frac{\eta_d\eta_l\lambda+\varrho}{\omega_m}\frac{\pi_m\omega_m}{\eta_d(1-\eta_l r)\lambda-\lambda_L/\eta_c-\varrho r-g(\delta-1)}>0$ and $\partial\hat{e}_m(r,\lambda)/\partial\lambda=-\frac{l(r)}{\omega_m}\frac{\pi_m\omega_m}{\eta_d(1-\eta_l r)\lambda-\lambda_L/\eta_c-\varrho r-g(\delta-1)}<0$, it can be shown that $\hat{e}_m(r,\lambda)$ is strictly increasing in r and decreasing in λ for any $m\in\{R,P\}$, $r>0$, and $\lambda>0$. Furthermore, the second-order partial derivative of $\hat{e}_m(r,\lambda)$ with respect to λ is $\partial^2\hat{e}_m(r,\lambda)/\partial\lambda^2=\frac{l^2(r)}{\omega_m(\eta_d(1-\eta_l r)\lambda-\lambda_L/\eta_c-\varrho r-g(\delta-1))^2}>0$. Since $\hat{e}_m(r,\lambda)$ is convex in λ, the energy that type-m CSEV drivers are willing to share, i.e., $e-\hat{e}_m(r,\lambda)$, is concave in λ.

(2) Expression and property of the maximum distance $\hat{r}_m(\overline{e}-\underline{e},\lambda)$.

The maximum possible distance within which a CSEV driver is willing to share energy is specified by a CSEV that has a full SOC $\overline{e}-\underline{e}$. This maximum distance, denoted by $\hat{r}_m(\overline{e}-\underline{e},\lambda)$, is the solution to $\hat{e}_m(r,\lambda)=\overline{e}-\underline{e}$. To determine the explicit formula for $\hat{r}_m(\overline{e}-\underline{e},\lambda)$, we solve the equation $\hat{e}_m(r,\lambda)=\overline{e}-\underline{e}$, yielding:

$$\hat{r}_m(\overline{e}-\underline{e},\lambda)=\frac{1}{\eta_l\eta_d\lambda+\varrho}\big(\eta_d\lambda-\lambda_L/\eta_c-g(\delta-1)-\pi_m w_m\exp(-w_m(\overline{e}-\underline{e}))\big),\quad \forall m\in\{R,P\}.$$

Note that $\hat{r}_m(\overline{e}-\underline{e},\lambda)$ is a strictly monotonic increasing and concave function of λ for any $m\in\{R,P\}$, and $\lambda>0$. This monotonicity can be verified by taking the first-order partial derivative with respect to λ, i.e., $\partial\hat{r}_m(\overline{e}-\underline{e},\lambda)/\partial\lambda=\frac{\eta_d[\varrho+\eta_l\lambda_L/\eta_c+\eta_l g(\delta-1)+\eta_l\pi_m w_m\exp(-w_m(\overline{e}-\underline{e}))]}{(\eta_l\eta_d\lambda+\varrho)^2}>0$. The concavity can be verified by taking the second-order partial derivative with respect to λ, i.e., $\partial^2\hat{r}_m(\overline{e}-\underline{e},\lambda)/\partial\lambda^2=\frac{-2\eta_d\eta_l[\eta_d\varrho+\eta_d\eta_l(\lambda_L/\eta_c+g(\delta-1)+\pi_m w_m\exp(-w_m(\overline{e}-\underline{e})))]}{(\eta_l\eta_d\lambda+\varrho)^3}<0$.

(3) Expressions of $\underline{\lambda}$ and $\overline{\lambda}$.

As $\hat{r}_m(\overline{e}-\underline{e},\lambda)$ is strictly increasing in λ, we use $\underline{\lambda}_m$ to denote the lower-bound price of λ for crowdsourcing type-m CSEVs, which is the solution to $\hat{r}_m(\overline{e}-\underline{e},\lambda)=0$. We derive $\underline{\lambda}_m$ that makes $\hat{r}_m(\overline{e}-\underline{e},\lambda)$ non-negative as follows:

$$\underline{\lambda}_m=\Big(\lambda_L+\eta_c\big(g(\varrho-1)+\pi_m w_m\exp(-w_m(\overline{e}-\underline{e}))\big)\Big)/\eta,\quad \forall m\in\{R,P\}. \tag{A.1}$$

To ensure that $\hat{r}_m(\overline{e}-\underline{e},\lambda)$ is non-negative for any type-m, we set $\underline{\lambda} \triangleq \max\{\underline{\lambda}_R, \underline{\lambda}_P\}$. Next, as $\hat{e}_m(r,\lambda)$ is strictly increasing in r and decreasing in λ, we use $\overline{\lambda}_m$ to denote the upper-bound price of λ for crowdsourcing type-m CSEVs, which is the solution to $\hat{e}_m(0,\lambda)=0$. Solving this equation yields $\overline{\lambda}_m$ as follows:

$$\overline{\lambda}_m = (\pi_m\omega_m + \lambda_L/\eta_c + g(\delta-1))/\eta_d, \quad \forall m\{R,P\}.$$

We set $\overline{\lambda} \triangleq \min\{\overline{\lambda}_R, \overline{\lambda}_P\}$ to ensure that $\hat{e}_m(r,\lambda)$ is non-negative for any type-m. Consequently, we obtain the explicit upper and lower bounds on the uniform price λ that make the integration limits in Equation (5) valid.

In Section 4.2, Assumption 2 establishes a key technical condition. This condition ensures that the community can crowdsource positive energy from CSEVs. **The derivation of the technical condition in Assumption 2** immediately follows from the fact that the peak price λ_H should be at least greater than the minimum crowdsourcing price $\underline{\lambda}_m$ defined in Equation (A.1). Otherwise the community would prefer to procure energy directly from the grid at the peak price λ_H rather than via CSEVs.

Proof of Proposition 1. To show that $G(\lambda)$ is monotonically increasing in λ, we examine the first-order derivative of $G(\lambda)$ with respect to λ

$$\begin{aligned}\frac{\mathrm{d}G(\lambda)}{\mathrm{d}\lambda} = &\sum_{m\in\{R,P\}} \int_0^{\hat{r}_m(\overline{e}-\underline{e},\lambda)} \int_{\hat{e}_m(r,\lambda)}^{\overline{e}-\underline{e}} -\frac{\partial \hat{e}_m(r,\lambda)}{\partial\lambda} l(r) n_m(e,r)\mathrm{d}r\mathrm{d}e \\ &+ \frac{\partial \hat{r}_m(\overline{e}-\underline{e},\lambda)}{\partial \lambda} \int_{\hat{e}_m(\hat{r}_m(\overline{e}-\underline{e},\lambda),\lambda)}^{\overline{e}-\underline{e}} \big(e - \hat{e}_m(\hat{r}_m(\overline{e}-\underline{e},\lambda),\lambda)\big) l(\hat{r}_m(\overline{e}-\underline{e},\lambda)) n_m(e,\hat{r}_m(\overline{e}-\underline{e},\lambda))\mathrm{d}e.\end{aligned} \tag{A.2}$$

According to the expressions and properties derived for $\hat{e}_m(r,\lambda)$ and $\hat{r}_m(\overline{e}-\underline{e},\lambda)$, both the first and second terms on the right side of Equation (A.2) are positive. Therefore, we conclude that $G(\lambda)$ is a strictly increasing function. □

A.2. Optimal Uniform Price

Proof of Theorem 1. To provide the optimal crowdsourcing scheme, i.e., the optimal crowdsourcing amount $h^*(b)$ and price $\lambda^*(b)$ for any residual demand $b>0$, we first prove that the piecewise function $W(h,b)$ is strictly decreasing in h when $h\le G(\lambda_X)$ and strictly convex when $h>G(\lambda_X)$. We then derive a closed-form expression for $h^*(b)$ and prove its existence and uniqueness.

(1) The properties of the piecewise function $W(h,b)$ with respect to h.

By putting $\lambda(h) \triangleq \max\{G^{-1}(h), \lambda_X\}$ defined in Section 4.2 into $W(h,b)$, the first-order and second-order derivatives of $W(h,b)$ with respect to h are

$$\frac{\partial W(h,b)}{\partial h} = \frac{\mathrm{d}\big(\lambda(h)h\big)}{\mathrm{d}h} - \lambda_H = \begin{cases} \lambda_X - \lambda_H, & \text{if } h \le G(\lambda_X), \\ \mathrm{d}\big(G^{-1}(h)h\big)/\mathrm{d}h - \lambda_H, & \text{otherwise,}\end{cases}$$

$$\frac{\partial^2 W(h,b)}{\partial h^2} = \frac{\mathrm{d}^2\big(\lambda(h)h\big)}{\mathrm{d}h^2} = \begin{cases} 0, & \text{if } h \le G(\lambda_X), \\ \mathrm{d}^2\big(G^{-1}(h)h\big)/\mathrm{d}h^2, & \text{otherwise.}\end{cases}$$

From Section 4.2, we know that λ_X is strictly less than λ_H. Because $\partial W(h,b)/\partial h<0$ and $\partial^2 W(h,b)/\partial h^2 = 0$ for any $h\le G(\lambda_X)$, $W(h,b)$ is strictly linear and monotonically decreasing in h if $h\le G(\lambda_X)$.

Next, we focus on the situation where $h>G(\lambda_X)$, i.e., $\lambda(h)=G^{-1}(h)$. We use λ' and G' to denote the first-order derivatives of functions λ and G, respectively. Similarly, denote λ'' and G'' as the second-order derivatives of functions λ and G, respectively. By taking the first and second derivatives of h on both sides of $G(\lambda(h))=h$, we have $G'(\lambda(h))\cdot\lambda'(h)=1$ and $G''(\lambda(h))[\lambda'(h)]^2+G'(\lambda(h))\lambda''(h)=0$, which imply that

$$\lambda'(h)=\frac{1}{G'(\lambda(h))}, \tag{A.3}$$

$$\lambda''(h)=-\frac{G''(\lambda(h))\big(\lambda'(h)\big)^2}{G'(\lambda(h))}=-\frac{G''(\lambda(h))}{\big(G'(\lambda(h))\big)^3}. \tag{A.4}$$

The first-order derivative of crowdsourcing cost function $\lambda(h)h$ is $\mathrm{d}\big(\lambda(h)h\big)/\mathrm{d}h=\lambda'(h)h+\lambda(h)$. By putting $G'(\lambda(h))>0$ obtained from Proposition 1 into Equation (A.3), we can derive $\mathrm{d}\big(\lambda(h)h\big)/\mathrm{d}h>0$ from $\lambda'(h)>0$.

The second-order derivative of crowdsourcing cost function $\lambda(h)h$ with respect to h is $\mathrm{d}^2\big(\lambda(h)h\big)/\mathrm{d}h^2=\lambda''(h)h+2\lambda'(h)$. According to Equations (A.3) and (A.4) and the log-concavity of $G(\lambda)$,

$$\begin{aligned}\frac{\mathrm{d}^2\big(\lambda(h)h\big)}{\mathrm{d}h^2}&=\frac{2\big(G'(\lambda(h))\big)^2-G(\lambda(h))G''(\lambda(h))}{\big(G'(\lambda(h))\big)^3}\\&=\frac{1}{G'(\lambda(h))}\left(1-\frac{\mathrm{d}^2\log(G(\lambda(h)))}{\mathrm{d}\lambda(h)^2}\cdot\Big(\frac{G(\lambda(h))}{G'(\lambda(h))}\Big)^2\right),\end{aligned} \tag{A.5}$$

where the second-order derivative of $\log(G(\lambda))$ is

$$\frac{\mathrm{d}^2\log(G(\lambda))}{\mathrm{d}\lambda^2}=\frac{G''(\lambda)G(\lambda)-\big(G'(\lambda)\big)^2}{\big(G(\lambda)\big)^2}\le 0. \tag{A.6}$$

By substituting Inequality (A.6) into Equation (A.5), $\mathrm{d}^2\big(\lambda(h)h\big)/\mathrm{d}h^2>0$, which implies $W(h,b)$ is strictly convex in h when $h>G(\lambda_X)$. Therefore, we conclude that the piecewise function $W(h,b)$ is strictly decreasing in h when $h\le G(\lambda_X)$ and strictly convex when $h>G(\lambda_X)$.

(2) The existence and uniqueness of the optimal crowdsourcing amount $h^*(b)$.

To prove the existence and uniqueness of $h^*(b)$, we first characterize the minimum of $W(h,b)$ based on its properties and then derive $h^*(b)$ for three different residual demand scenarios.

For $h\le G(\lambda_X)$, $W(h,b)$ is strictly decreasing in h. Thus, $W(h,b)$ attains its minimum at the right endpoint $h=G(\lambda_X)$, denoted as $W(G(\lambda_X),b)$. For $h>G(\lambda_X)$, $W(h,b)$ is strictly convex. Thus, $W(h,b)$ attains its minimum at a unique point $\overline{h}$ where its first derivative equals zero, i.e., $\overline{h}$ is the unique root of the equation $\mathrm{d}(\lambda(h)h)/\mathrm{d}h=\lambda_H$.

Based on the characterization of the minimizer of $W(h,b)$, we analyze $h^*(b)$ in the following three cases. If $b\le G(\lambda_X)$, $h^*(b)=b$ because $W(h,b)$ reaches its minimum at $h=G(\lambda_X)$ and $h\le b$, i.e., $h=\min\{b,G(\lambda_X)\}$. If $G(\lambda_X)<b\le\overline{h}$, $h^*(b)=b$ because $W(h,b)$ reaches its minimum at $\overline{h}$ and $h\le b$, i.e., $h=\min\{b,\overline{h}\}$. If $\overline{h}<b$, $h^*(b)=\overline{h}$ because $W(h,b)$ reaches its minimum at $\overline{h}$. In summary, there is a unique optimal crowdsourcing amount $h^*(b)$, which can be expressed as $\min\{b,\overline{h}\}$. □

Proof of Proposition 2. Before proving that $\widetilde{\lambda}(b)$ is strictly less than λ_H and increases in b, we first show the expression of $\widetilde{\lambda}(b)$. According to $h^*(b)=\min\{b,\overline{h}\}$ proposed in Theorem 1, the optimal uniform price is

$$\lambda^*(b)=\begin{cases}\lambda_X, & \text{if } 0<b\le G(\lambda_X),\\ \lambda(b), & \text{if } G(\lambda_X)<b\le\overline{h},\\ \lambda(\overline{h}), & \text{otherwise.}\end{cases}$$

By substituting the expressions of $h^*(b)$ and $\lambda^*(b)$ into $\widetilde{\lambda}(b)=W(h^*(b),b)/b$, $\widetilde{\lambda}(b)$ for any $b>0$ is given by

$$\widetilde{\lambda}(b)=\begin{cases}\lambda_X, & \text{if } 0<b\le G(\lambda_X),\\ \lambda(b), & \text{if } G(\lambda_X)<b\le\overline{h},\\ \lambda_H+(\lambda(\overline{h})-\lambda_H)\overline{h}/b, & \text{otherwise.}\end{cases}$$

(i) To show that $\widetilde{\lambda}(b)$ is strictly less than λ_H, consider three cases.

(i-a) If $0 < b \le G(\lambda_X)$, $\widetilde{\lambda}(b) < \lambda$ because $\lambda_X < \lambda_H$ proposed in Section 4.2. (i-b) If $G(\lambda_X) < b \le \overline{h}$, $\widetilde{\lambda}(b) \le \lambda(\overline{h})$ because $\lambda'(b) > 0$ follows from the proof process of Theorem 1. We can obtain $\lambda(\overline{h}) < \lambda_H$ from the definition of $\overline{h}$, i.e., $\lambda'(\overline{h})\overline{h} + \lambda(\overline{h}) = \lambda_H$, where $\lambda'(\overline{h}) > 0$ and $\overline{h} > 0$. Thus, we prove that $\widetilde{\lambda}(b) < \lambda_H$. (i-c) If $\overline{h} < b$, $\widetilde{\lambda}(b) < \lambda_H$ because $\lambda(\overline{h}) < \lambda_H$.

(ii) To show that $\widetilde{\lambda}(b)$ increases in b, note that the first-order derivative of $\widetilde{\lambda}(b)$ with respect to b is

$$\frac{\mathrm{d}\widetilde{\lambda}(b)}{\mathrm{d}b} = \begin{cases} 0, & \text{if } 0 < b \le G(\lambda_X), \\ \lambda'(b), & \text{if } G(\lambda_X) < b \le \overline{h}, \\ \big(\lambda_H - \lambda(\overline{h})\big)\overline{h}/b^2, & \text{otherwise.} \end{cases}$$

We can derive $\mathrm{d}\widetilde{\lambda}(b)/\mathrm{d}b \ge 0$ because $\lambda' > 0$ and $\lambda_H - \lambda(\overline{h}) > 0$. Thus, we prove that $\widetilde{\lambda}(b)$ increases in b. □

Appendix B: Stationary Storage Sharing

B.1. Storage-Present Omni Sharing

Proof of Lemma 1. By definition from Section 5.1, to show coalition rationality is to show that $\sum_{i\in\mathcal{S}} \beta_{i,R} \le V_R(\mathcal{S})$ for any $\mathcal{S} \subseteq \mathcal{N}$. From the definitions of $\boldsymbol{\beta}_R$ and V_R in Section 5.3, for any coalition $\mathcal{S} \in \mathcal{N}$, there are $V_R(\mathcal{S}) = (\lambda_C + \lambda_L)c_{\mathcal{S}} - \lambda_L(c_{\mathcal{S}} - q_{\mathcal{S}}/\eta)^+ + \lambda_R(b_{\mathcal{S}}(c_{\mathcal{S}}))(q_{\mathcal{S}} - \eta c_{\mathcal{S}})^+$ and

$$\begin{aligned}\sum_{i\in\mathcal{S}} \beta_{i,R} &= (\lambda_C + \lambda_L)\sum_{i\in\mathcal{S}} c_i + \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))\sum_{i\in\mathcal{S}}(q_i - \eta c_i) \\ &= (\lambda_C + \lambda_L)c_{\mathcal{S}} + \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))(q_{\mathcal{S}} - \eta c_{\mathcal{S}}) \\ &= (\lambda_C + \lambda_L)c_{\mathcal{S}} + \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))\big(-(\eta c_{\mathcal{S}} - q_{\mathcal{S}})^+ + (q_{\mathcal{S}} - \eta c_{\mathcal{S}})^+\big) \\ &= (\lambda_C + \lambda_L)c_{\mathcal{S}} - \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))(\eta c_{\mathcal{S}} - q_{\mathcal{S}})^+ + \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))(q_{\mathcal{S}} - \eta c_{\mathcal{S}})^+.\end{aligned}$$

If $\eta c_{\mathcal{S}} \ge q_{\mathcal{S}}$, $V_R(\mathcal{S}) = (\lambda_C + \lambda_L)c_{\mathcal{S}} - \lambda_L(c_{\mathcal{S}} - q_{\mathcal{S}}/\eta)$ and $\sum_{i\in\mathcal{S}} \beta_{i,R} = (\lambda_C + \lambda_L)c_{\mathcal{S}} - \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))(\eta c_{\mathcal{S}} - q_{\mathcal{S}})$. From the definition of $\lambda_R(\cdot)$ in Section 5.3 and Assumption 2, $\lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}})) > \lambda_L/\eta$. Thus, $\sum_{i\in\mathcal{S}} \beta_{i,R} \le V_R(\mathcal{S})$, $\forall \mathcal{S} \subseteq \mathcal{N}$.
If $\eta c_{\mathcal{S}} < q_{\mathcal{S}}$, $V_R(\mathcal{S}) = (\lambda_C + \lambda_L)c_{\mathcal{S}} + \lambda_R(b_{\mathcal{S}}(c_{\mathcal{S}}))(q_{\mathcal{S}} - \eta c_{\mathcal{S}})$ and $\sum_{i\in\mathcal{S}} \beta_{i,R} = (\lambda_C + \lambda_L)c_{\mathcal{S}} + \lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}}))(q_{\mathcal{S}} - \eta c_{\mathcal{S}})$. Because $b_{\mathcal{S}}(c_{\mathcal{S}}) = (q_{\mathcal{S}} - \eta c_{\mathcal{S}})^+ + \sum_{\mathcal{M}\in\{\mathcal{S}_1,\ldots,\mathcal{S}_M\}}(q_{\mathcal{M}} - \eta c_{\mathcal{M}})^+$ and $b_{\mathcal{N}}(c_{\mathcal{N}}) = (q_{\mathcal{N}} - \eta c_{\mathcal{N}})^+$, there is $b_{\mathcal{N}}(c_{\mathcal{N}}) \le b_{\mathcal{S}}(c_{\mathcal{S}})$ for any $\mathcal{S} \subseteq \mathcal{N}$. We know that $\lambda_R(\cdot)$ is a non-decreasing function according to the definition of $\lambda_R(\cdot)$ in Section 5.3 and the non-decreasing property of $\widetilde{\lambda}(\cdot)$ in Proposition 2. Based on $b_{\mathcal{N}}(c_{\mathcal{N}}) \le b_{\mathcal{S}}(c_{\mathcal{S}})$ and the non-decreasing property of $\lambda_R(\cdot)$, there is $\lambda_R(b_{\mathcal{N}}(c_{\mathcal{N}})) \le \lambda_R(b_{\mathcal{S}}(c_{\mathcal{S}}))$ for any $\mathcal{S} \subseteq \mathcal{N}$. Thus, $\sum_{i\in\mathcal{S}} \beta_{i,R} \le V_R(\mathcal{S})$ for any $\mathcal{S} \subseteq \mathcal{N}$. Consequently, we conclude that the constructed allocation $\boldsymbol{\beta}_R$ is coalition rational. □

B.2. Joint Storage-Planning & Omni Sharing

Proof of Theorem 3. We first derive the closed-form solution of the optimal total storage capacity, and then we prove the uniqueness of the optimal solution in the following.

(1) The optimal total storage capacity $c^*(\mathcal{N})$ is $\Omega^{-1}(\gamma)/\eta$.

According to the definition of $\widetilde{\lambda}(\cdot)$ in Section 4.3, $V_{\mathcal{S}}(c_{\mathcal{S}}, q_{\mathcal{S}})$ defined in Equation (8) with $\mathcal{S} = \mathcal{N}$ equals to

$$\begin{aligned}\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}}, q_{\mathcal{N}})] =& (\lambda_C + \lambda_L)c_{\mathcal{N}} - \frac{\lambda_L}{\eta}\int_0^{\eta c_{\mathcal{N}}} \eta c_{\mathcal{N}} - q_{\mathcal{N}} \mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) + \int_{\eta c_{\mathcal{N}}}^{+\infty} \widetilde{\lambda}(q_{\mathcal{N}} - \eta c_{\mathcal{N}})(q_{\mathcal{N}} - \eta c_{\mathcal{N}})\mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) \\ =& (\lambda_C + \lambda_L)c_{\mathcal{N}} - \frac{\lambda_L}{\eta}\int_0^{\eta c_{\mathcal{N}}} \eta c_{\mathcal{N}} - q_{\mathcal{N}} \mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) + \int_{\eta c_{\mathcal{N}}}^{\eta c_{\mathcal{N}} + \overline{h}} \lambda(q_{\mathcal{N}} - \eta c_{\mathcal{N}})(q_{\mathcal{N}} - \eta c_{\mathcal{N}})\mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) \\ &+ \int_{\eta c_{\mathcal{N}} + \overline{h}}^{+\infty} \lambda(\overline{h})\overline{h} + \lambda_H(q_{\mathcal{N}} - \eta c_{\mathcal{N}} - \overline{h})\mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}),\end{aligned}$$

where $F_{\mathcal{S}}(q_{\mathcal{S}})$ denotes the cumulative distribution function of random demand $q_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$, and the maximum crowdsourcing energy quantity $\overline{h}$ defined in Theorem 1 of Section 4.3 is independent of the community's demand and decision. The first-order derivative of $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$ with respect to $c_{\mathcal{N}}$ is

$$\begin{aligned}\frac{\mathrm{d}\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]}{\mathrm{d}c_{\mathcal{N}}}&=\lambda_C+\lambda_L-\lambda_L F_{\mathcal{N}}(\eta c_{\mathcal{N}})-\eta\lambda_E(\eta c_{\mathcal{N}})\big(F_{\mathcal{N}}(\eta c_{\mathcal{N}}+\overline{h})-F_{\mathcal{N}}(\eta c_{\mathcal{N}})\big)-\eta\lambda_H\big(1-F_{\mathcal{N}}(\eta c_{\mathcal{N}}+\overline{h})\big)\\&=\lambda_C+\lambda_L-\eta\lambda_H+(\eta\lambda_H-\lambda_L)F_{\mathcal{N}}(\eta c_{\mathcal{N}})+\eta\big(\lambda_H-\lambda_E(\eta c_{\mathcal{N}})\big)\big(F_{\mathcal{N}}(\eta c_{\mathcal{N}}+\overline{h})-F_{\mathcal{N}}(\eta c_{\mathcal{N}})\big),\end{aligned}$$

where $\lambda_E(x)=\mathbb{E}[\mathrm{d}\big(\lambda(h)h\big)/\mathrm{d}h|_{h=q_{\mathcal{N}}-x}|0<h\le\overline{h}]$ defined in Section 5.4 represents the expected marginal payment to CSEVs. From the first-order condition of $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$, i.e., $\mathrm{d}\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]/\mathrm{d}c_{\mathcal{N}}|_{c=c^*(\mathcal{N})}=0$,

$$F_{\mathcal{N}}(\eta c^*(\mathcal{N}))+\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\frac{\lambda_H-\lambda_E(\eta c^*(\mathcal{N}))}{\lambda_H-\lambda_L/\eta}=\frac{\lambda_H-(\lambda_C+\lambda_L)/\eta}{\lambda_H-\lambda_L/\eta},$$

where the left side of the equation is the value of the "CSEV-inflated CDF" $\Omega(x)$ at $x=\eta c^*(\mathcal{N})$, and the right side of the equation equals the critical fractile ratio γ. Therefore, we prove that $c^*(\mathcal{N})=\Omega^{-1}(\gamma)/\eta$.

(2) The optimal total storage capacity $c^*(\mathcal{N})$ is unique.

The optimal total storage capacity $c^*(\mathcal{N})$ is a unique solution if $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$ is a convex function of $c_{\mathcal{N}}$. We rearrange $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$, and define $x\triangleq q_{\mathcal{N}}-\eta c_{\mathcal{N}}$ based on the integration by substitution as follows:

$$\begin{aligned}\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]=&\frac{\lambda_C+\lambda_L}{\eta}\mathbb{E}[q_{\mathcal{N}}]+\frac{\lambda_C}{\eta}\int_0^{\eta c_{\mathcal{N}}}(\eta c_{\mathcal{N}}-q_{\mathcal{N}})\mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}})+\int_0^{\overline{h}}\big(\lambda(x)-\frac{1}{\eta}(\lambda_C+\lambda_L)\big)x\mathrm{d}F_{\mathcal{N}}(x+\eta c_{\mathcal{N}})\\&+\int_{\overline{h}}^{+\infty}\Big(\lambda(\overline{h})\overline{h}+\lambda_H(x-\overline{h})-\frac{1}{\eta}(\lambda_C+\lambda_L)x\Big)\mathrm{d}F_{\mathcal{N}}(x+\eta c_{\mathcal{N}}).\end{aligned}$$

For simplicity, we define $\Gamma_0(x)=\big(\lambda(x)-\frac{1}{\eta}(\lambda_L+\lambda_C)\big)x$ and $\Gamma_1(x)=\lambda(\overline{h})\overline{h}+\lambda_H(x-\overline{h})-\frac{1}{\eta}(\lambda_L+\lambda_C)x$, and denote the PDF of $q_{\mathcal{S}}$ by $f_{\mathcal{S}}(\cdot)$, $\forall\mathcal{S}\subseteq\mathcal{N}$. The first-order derivative of $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$ with respect to $c_{\mathcal{N}}$ is

$$\begin{aligned}\frac{\mathrm{d}\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]}{\mathrm{d}c_{\mathcal{N}}}=&\lambda_C F_{\mathcal{N}}(\eta c_{\mathcal{N}})-\eta\Big(\Gamma_0(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})|_0^{\overline{h}}-\Gamma_1(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})|_{\overline{h}}^{+\infty}\Big)\\=&\lambda_C F_{\mathcal{N}}(\eta c_{\mathcal{N}})-\eta\Gamma_1(+\infty)f_{\mathcal{N}}(+\infty),\end{aligned}$$

where the first equation follows from $\int_0^{\overline{h}}\Gamma_0(x)f'_{\mathcal{N}}(x+\eta c_{\mathcal{N}})\mathrm{d}x=\Gamma_0(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})|_0^{\overline{h}}-\int_0^{\overline{h}}\Gamma'_0(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})\mathrm{d}x$ and $\int_{\overline{h}}^{+\infty}\Gamma_1(x)f'_{\mathcal{N}}(x+\eta c_{\mathcal{N}})\mathrm{d}x=\Gamma_1(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})|_0^{\overline{h}}-\int_{\overline{h}}^{+\infty}\Gamma'_1(x)f_{\mathcal{N}}(x+\eta c_{\mathcal{N}})\mathrm{d}x$ based on the integration by parts. The second equation follows from $\Gamma_0(0)=0$ and $\Gamma_0(\overline{h})=\Gamma_1(\overline{h})$. Then, the second-order derivative of $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$ with respect to $c_{\mathcal{N}}$ is $\eta\lambda_C f_{\mathcal{N}}(\eta c_{\mathcal{N}})$. We conclude that $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$ is a convex function of $c_{\mathcal{N}}$ because $f_{\mathcal{N}}(\eta c_{\mathcal{N}})\ge 0$ for any given $c\ge 0$. Therefore, we prove that $c^*(\mathcal{N})$ is a unique solution. □

Proof of Corollary 1. Our goal is to compare $c^*(\mathcal{N})$ and $c^*_{P2P}(\mathcal{N})$. In Section 5.4, the closed-form optimal capacity of the grand coalition in the game $(\mathcal{N},V_{P2P,L})$ is $c^*_{P2P}(\mathcal{N})=F_{\mathcal{N}}^{-1}(\gamma)/\eta$, and that in the game $(\mathcal{N},V_L)$ is $c^*(\mathcal{N})=\Omega^{-1}(\gamma)/\eta$. By definition, $\Omega(x)\ge F_{\mathcal{N}}(x)$ because $\frac{\lambda_H-\lambda_E(x)}{\lambda_H-\lambda_L/\eta}\big(F_{\mathcal{N}}(x+\overline{h})-F_{\mathcal{N}}(x)\big)\ge 0$ for any given $x\ge 0$. From the monotonic property of $\Omega(\cdot)$ in the proof of Theorem 3, $\Omega(x)\ge F_{\mathcal{N}}(x)$ is equivalent to $\Omega^{-1}(\gamma)\le F_{\mathcal{N}}^{-1}(\gamma)$. Consequently, we can conclude that $c^*(\mathcal{N})\le c^*_{P2P}(\mathcal{N})$. □

Proof of Theorem 4. By putting the closed-form $c^*(\mathcal{N})$ proposed in Theorem 3 into $\mathbb{E}[V_{\mathcal{N}}(c_{\mathcal{N}},q_{\mathcal{N}})]$, we first derive the analytical expression of $V_L(\mathcal{N})$. Based on the analytical expressions of $V_{P2P,L}(\mathcal{N})$ and $V_L(\mathcal{N})$, we quantify the difference between $V_{P2P,L}(\mathcal{N})$ and $V_L(\mathcal{N})$, and prove $V_{P2P,L}(\mathcal{N})-V_L(\mathcal{N})>0$ in the following.

(1) Derive the analytical expression of $V_L(\mathcal{N})$.

By clustering the coefficients of $c^*(\mathcal{N})$, $V_L(\mathcal{N})$ can be expressed as

$$\begin{aligned}
V_L(\mathcal{N}) =& \Big(\lambda_C + \lambda_L - \lambda_L F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \eta\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big)\Big) c^*(\mathcal{N}) \\
&+ \frac{\lambda_L}{\eta} \int_0^{\eta c^*(\mathcal{N})} q_{\mathcal{N}} \mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) + \int_{\eta c^*(\mathcal{N})}^{\eta c^*(\mathcal{N})+\overline{h}} \lambda(q_{\mathcal{N}} - \eta c^*(\mathcal{N}))\big(q_{\mathcal{N}} - \eta c^*(\mathcal{N})\big) \mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) \\
&+ \lambda_H \int_{\eta c^*(\mathcal{N})+\overline{h}}^{+\infty} q_{\mathcal{N}} \mathrm{d}F_{\mathcal{N}}(q_{\mathcal{N}}) - \big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
=& \Big(\lambda_C + \lambda_L - \lambda_L F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \eta\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big)\Big) c^*(\mathcal{N}) \\
&+ \frac{\lambda_L}{\eta} \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} \leq \eta c^*(\mathcal{N})] F_{\mathcal{N}}(\eta c^*(\mathcal{N})) + \mathbb{E}[\lambda(h) h|_{q_{\mathcal{N}} - \eta c^*(\mathcal{N})} | 0 < h \leq \overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&+ \lambda_H \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} > \eta c^*(\mathcal{N}) + \overline{h}]\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) - \big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
=& \Big(\lambda_C + \lambda_L - \lambda_L F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \eta\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big)\Big) c^*(\mathcal{N}) \\
&+ \frac{\lambda_L}{\eta} \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} \leq \eta c^*(\mathcal{N})] F_{\mathcal{N}}(\eta c^*(\mathcal{N})) + \lambda_H \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} > \eta c^*(\mathcal{N})][1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))] \\
&- \big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
&- \big(\lambda_H - \lambda_W(\eta c^*(\mathcal{N}))\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N}) | \eta c^*(\mathcal{N}) < q_{\mathcal{N}} \leq \eta c^*(\mathcal{N}) + \overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&- \eta \lambda_H c^*(\mathcal{N})\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big),
\end{aligned} \tag{B.1}$$

where the last equation follows from the definition of average payment per kWh to CSEVs, i.e., $\lambda_W(x) \triangleq \mathbb{E}[\lambda(h) h|_{q_{\mathcal{N}} - \eta c^*(\mathcal{N})} | 0 < h \leq \overline{h}] / \mathbb{E}[h|_{q_{\mathcal{N}} - \eta c^*(\mathcal{N})} | 0 < h \leq \overline{h}]$.

The coefficient of the first term on the right side of Equation (B.1) is equivalent to

$$\begin{aligned}
&\lambda_C + \lambda_L - \lambda_L F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \eta\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
=& \lambda_H \eta(1 - \gamma) + \lambda_L \gamma - \lambda_L F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \eta\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
=& \eta\Big(\lambda_H F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - \frac{\lambda_L}{\eta} F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - (\lambda_H - \frac{\lambda_L}{\eta})\gamma\Big) \\
=& \eta\Big((\lambda_H - \frac{\lambda_L}{\eta})(F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \gamma) + \lambda_H(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N})))\Big) \\
=& \eta \lambda_E(\eta c^*(\mathcal{N}))\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big),
\end{aligned}$$

where the first equation follows from $\lambda_C + \lambda_L = \lambda_H \eta(1 - \gamma) + \lambda_L \gamma$ which can be derived from $\gamma = \big(\lambda_H - (\lambda_C + \lambda_L)/\eta\big)/(\lambda_H - \lambda_L)$, and the last equation follows from $(\lambda_H - \lambda_L/\eta)(F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \gamma) = -[F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))](\lambda_H - \lambda_E(\eta c^*(\mathcal{N})))$ derived from the expression of the optimal total storage capacity $c^*(\mathcal{N})$ in Theorem 3. Therefore, the analytical expression of $V_L(\mathcal{N})$ is

$$\begin{aligned}
V_L(\mathcal{N}) =& \frac{\lambda_L}{\eta} \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} \leq \eta c^*(\mathcal{N})] F_{\mathcal{N}}(\eta c^*(\mathcal{N})) + \lambda_H \mathbb{E}[q_{\mathcal{N}} | q_{\mathcal{N}} > \eta c^*(\mathcal{N})]\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&- \big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1 - F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h})\big) \\
&- \big(\lambda_H - \lambda_W(\eta c^*(\mathcal{N}))\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N}) | \eta c^*(\mathcal{N}) < q_{\mathcal{N}} \leq \eta c^*(\mathcal{N}) + \overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&- \eta\big(\lambda_H - \lambda_E(\eta c^*(\mathcal{N}))\big) c^*(\mathcal{N})\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N}) + \overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)
\end{aligned}$$

(2) Quantify the difference between $V_{P2P,L}(\mathcal{N})$ and $V_L(\mathcal{N})$.

According to the proof of Equation (10) and the analytical expression of $V_L(\mathcal{N})$,

$$\begin{aligned}
&V_{P2P,L}(\mathcal{N}) - V_L(\mathcal{N}) \\
\overset{(1)}{=}&\frac{\lambda_L}{\eta}\mathbb{E}[q_{\mathcal{N}}|q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) + \lambda_H \mathbb{E}[q_{\mathcal{N}}|q_{\mathcal{N}} > \eta c^*_{P2P}(\mathcal{N})]\big(1-F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))\big) \\
&-\frac{\lambda_L}{\eta}\mathbb{E}[q_{\mathcal{N}}|q_{\mathcal{N}} \le \eta c^*(\mathcal{N})]F_{\mathcal{N}}(\eta c^*(\mathcal{N})) - \lambda_H \mathbb{E}[q_{\mathcal{N}}|q_{\mathcal{N}} > \eta c^*(\mathcal{N})][1-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))] \\
&+\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})\big) \\
&+\big(\lambda_H - \lambda_W(\eta c^*(\mathcal{N}))\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&+\eta\big(\lambda_H - \lambda_E(\eta c^*(\mathcal{N}))\big)c^*(\mathcal{N})\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
\overset{(2)}{=}&-(\lambda_H - \lambda_L/\eta)\mathbb{E}[q_{\mathcal{N}}|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&+\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})\big) \\
&+\big(\lambda_H - \lambda_W(\eta c^*(\mathcal{N}))\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \qquad \text{(B.2)} \\
&+\eta(\lambda_H - \lambda_L/\eta)c^*(\mathcal{N})\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
\overset{(3)}{=}&\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big) \\
&+\big(\lambda_H - \lambda_W(\eta c^*(\mathcal{N}))\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&-(\lambda_H - \lambda_L/\eta)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
\overset{(4)}{=}&\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big) \\
&+\lambda_H\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))\big) \\
&-\lambda_W(\eta c^*(\mathcal{N}))\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&+\frac{\lambda_L}{\eta}\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big).
\end{aligned}$$

By integrating the first four terms of the first equation, we obtain the first term in the second equation. From the critical fractile formulas defined in the game $(\mathcal{N}, V_{P2P,L})$ and the game $(\mathcal{N}, V_L)$, we can obtain the last term in the second equation by replacing $F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h}) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))$ with $\frac{\lambda_H - \lambda_L/\eta}{\lambda_H - \lambda_E(\eta c^*(\mathcal{N}))}\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)$. The third equation is obtained by integrating the first and last terms of the second equation.

(3) Prove $V_{P2P,L}(\mathcal{N}) - V_L(\mathcal{N}) > 0$.

Based on the analytical expression of the difference between $V_{P2P,L}(\mathcal{N})$ and $V_L(\mathcal{N})$,

$$\begin{aligned}
&V_{P2P,L}(\mathcal{N}) - V_L(\mathcal{N}) \\
=&\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big) \\
&+\lambda_H\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big) - F_{\mathcal{N}}\big(\eta c^*_{P2P}(\mathcal{N})\big)\big) \\
&-\lambda_W(\eta c^*(\mathcal{N}))\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big) - F_{\mathcal{N}}\big(\eta c^*_{P2P}(\mathcal{N})\big)\big) \\
&-\lambda_W(\eta c^*(\mathcal{N}))\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
&+\frac{\lambda_L}{\eta}\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N})) - F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big) \\
=&\big(\lambda_H - \lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big) \\
&+\big(\lambda_H - \lambda_W\big(\eta c^*(\mathcal{N})\big)\big)\mathbb{E}[q_{\mathcal{N}} - \eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N}) < q_{\mathcal{N}} \le \eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big) - F_{\mathcal{N}}\big(\eta c^*_{P2P}(\mathcal{N})\big)\big)
\end{aligned}$$

$$
\begin{aligned}
&-\big(\lambda_W\big(\eta c^*(\mathcal{N})\big)-\lambda_L/\eta\big)\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\\
\ge&\big(\lambda_H-\lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big)\\
&+\big(\lambda_H-\lambda_E\big(\eta c^*(\mathcal{N})\big)\big)\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)-F_{\mathcal{N}}\big(\eta c^*_{P2P}(\mathcal{N})\big)\big)\\
&-\big(\lambda_H-\lambda_L/\eta\big)\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\\
=&\big(\lambda_H-\lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big)\\
&+\big(\lambda_H-\lambda_L/\eta\big)\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\\
&-\big(\lambda_H-\lambda_L/\eta\big)\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\\
=&\big(\lambda_H-\lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)\big)+\big(\lambda_H-\lambda_L/\eta\big)\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)\\
&\times\Big(\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]-\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]\Big)\\
>&0,
\end{aligned}
$$

where the first equation follows from $\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)=\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*_{P2P}(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]\big(F_{\mathcal{N}}\big(\eta c^*(\mathcal{N})+\overline{h}\big)-F_{\mathcal{N}}\big(\eta c^*_{P2P}(\mathcal{N})\big)\big)+\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)$. By combining same terms, we obtain the second equation. The first inequality follows from $\lambda_H-\lambda_W(\eta c^*(\mathcal{N}))\ge\lambda_H-\lambda_E(\eta c^*(\mathcal{N}))$ and $\lambda_W(\eta c^*(\mathcal{N}))-\lambda_L/\eta<\lambda_H-\lambda_L/\eta$. Because the convexity of $\lambda(h)h$ for any given $h\ge0$ derived from Proposition 1 implies that the expected marginal payment to CSEVs is larger than the average payment per kWh to CSEVs, i.e., $\lambda_E(\eta c^*(\mathcal{N}))\ge\lambda_W(\eta c^*(\mathcal{N}))$, there is $\lambda_H-\lambda_W(\eta c^*(\mathcal{N}))\ge\lambda_H-\lambda_E(\eta c^*(\mathcal{N}))$. From $\lambda_H>\widetilde{\lambda}(b)$ for any $b\ge0$ proposed in Proposition 2, we can infer that the peak energy price is larger than the average payment per kWh to CSEVs, i.e., $\lambda_H>\lambda_W(\eta c^*(\mathcal{N}))$. By replacing $F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))$ with $\frac{\lambda_H-\lambda_L/\eta}{\lambda_H-\lambda_E(\eta c^*(\mathcal{N}))}\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)$, we obtain the third equation. The last inequality holds for: (i) the first term in the second equation is larger than 0, i.e., $\big(\lambda_H-\lambda(\overline{h})\big)\overline{h}\big(1-F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})\big)>0$, because the maximum payment per kWh to CSEVs $\lambda(\overline{h})$ is strictly less than the peak price λ_H and $F_{\mathcal{N}}(\eta c^*(\mathcal{N})+\overline{h})$ is less than 1; (ii) $(\lambda_H-\lambda_L/\eta)\big(F_{\mathcal{N}}(\eta c^*_{P2P}(\mathcal{N}))-F_{\mathcal{N}}(\eta c^*(\mathcal{N}))\big)>0$ because of $c^*_{P2P}(\mathcal{N})\ge c^*(\mathcal{N})$ shown in Corollary 1; (iii) $\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*(\mathcal{N})+\overline{h}]-\mathbb{E}[q_{\mathcal{N}}-\eta c^*(\mathcal{N})|\eta c^*(\mathcal{N})<q_{\mathcal{N}}\le\eta c^*_{P2P}(\mathcal{N})]>0$ because $\overline{h}$ is large enough. Overall, we provide the analytical expression of $V_{P2P,L}(\mathcal{N})-V_L(\mathcal{N})$ and prove that $V_{P2P,L}(\mathcal{N})-V_L(\mathcal{N})$ is positive. □

Derivation of the dual problem of Equation (13). To derive the dual of the auxiliary game's cost function $\hat{V}_L(\mathcal{S})$ defined in Equation (13), we first focus on a discrete approximation of the demand distribution. Consider a discrete probability space Υ, where each scenario υ has probability $p(\upsilon)$ satisfying $\sum_{\upsilon\in\Upsilon}p(\upsilon)=1$. For each scenario $\upsilon\in\Upsilon$, we define the random demand $q_{\mathcal{S}}(\upsilon)$, as well as $u(\upsilon)\triangleq(\eta c_{\mathcal{S}}-q_{\mathcal{S}}(\upsilon))^+$ and $y(\upsilon)\triangleq(q_{\mathcal{S}}(\upsilon)-\eta c_{\mathcal{S}})^+$. Substituting these into the objective, the primal problem defined in Equation (13) is equivalent to the following linear program:

$$
\begin{aligned}
\min_{c_{\mathcal{S}},u(\upsilon),y(\upsilon)}\ &(\lambda_C+\lambda_L)c_{\mathcal{S}}+\sum_{\upsilon\in\Upsilon}p(\upsilon)\big(-\frac{\lambda_L}{\eta}u(\upsilon)+\hat{\lambda}_{\mathcal{N}}y(\upsilon)\big)\\
\text{s.t.}\quad &\eta c_{\mathcal{S}}-u(\upsilon)+y(\upsilon)=q_{\mathcal{S}}(\upsilon), &&\forall\upsilon\in\Upsilon,\\
&c_{\mathcal{S}}\ge0,\\
&u(\upsilon)\ge0,y(\upsilon)\ge0, &&\forall\upsilon\in\Upsilon.
\end{aligned}
$$

This is a linear program with decision variables $c_{\mathcal{S}}$, $u(\upsilon)$, and $y(\upsilon)$. Its dual problem is constructed by introducing a dual variable $\alpha_{\mathcal{S}}(\upsilon)$ for each equality constraint. The resulting dual problem is:

$$\begin{aligned}
\max_{\alpha_{\mathcal{S}}(\upsilon)} & \sum_{\upsilon\in\Upsilon}\alpha_{\mathcal{S}}(\upsilon)q_{\mathcal{S}}(\upsilon) \\
\text{s.t.} \quad & \eta\sum_{\upsilon\in\Upsilon}\alpha_{\mathcal{S}}(\upsilon)\le\lambda_C+\lambda_L, \\
& p(\upsilon)\lambda_L/\eta\le\alpha_{\mathcal{S}}(\upsilon)\le p(\upsilon)\hat{\lambda}_{\mathcal{N}}, \qquad \forall\upsilon\in\Upsilon.
\end{aligned}$$

Let $\theta_{\mathcal{S}}(\upsilon)=\alpha_{\mathcal{S}}(\upsilon)/p(\upsilon)$ for any $\upsilon\in\Upsilon$. The dual problem is equivalent to

$$\begin{aligned}
\max_{\theta_{\mathcal{S}}(\upsilon)} & \sum_{\upsilon\in\Upsilon}p(\upsilon)\theta_{\mathcal{S}}(\upsilon)q_{\mathcal{S}}(\upsilon) \\
\text{s.t.} \quad & \sum_{\upsilon\in\Upsilon}p(\upsilon)\theta_{\mathcal{S}}(\upsilon)\le(\lambda_C+\lambda_L)/\eta, \\
& \lambda_L/\eta\le\theta_{\mathcal{S}}(\upsilon)\le\hat{\lambda}_{\mathcal{N}}, \qquad \forall\upsilon\in\Upsilon.
\end{aligned}$$

Since $\sum_{\upsilon\in\Upsilon}p(\upsilon)\theta_{\mathcal{S}}(\upsilon)q_{\mathcal{S}}(\upsilon)=\mathbb{E}[\theta_{\mathcal{S}}q_{\mathcal{S}}(\upsilon)]$ and $\sum_{\upsilon\in\Upsilon}p(\upsilon)\theta_{\mathcal{S}}(\upsilon)=\mathbb{E}[\theta_{\mathcal{S}}]$, the dual problem is simplified as

$$\begin{aligned}
\max_{\theta_{\mathcal{S}}(\upsilon)} & \mathbb{E}[\theta_{\mathcal{S}}(\upsilon)q_{\mathcal{S}}(\upsilon)] \\
\text{s.t.} \quad & \mathbb{E}[\theta_{\mathcal{S}}(\upsilon)]\le(\lambda_C+\lambda_L)/\eta, \\
& \lambda_L/\eta\le\theta_{\mathcal{S}}(\upsilon)\le\hat{\lambda}_{\mathcal{N}}, \qquad \forall\upsilon\in\Upsilon.
\end{aligned}$$

Based on the dual problem in discrete situations, the dual problem with continuous stochastic demand can be expressed as

$$\begin{aligned}
\max_{\theta_{\mathcal{S}}(q_{\mathcal{S}})} & \mathbb{E}[\theta_{\mathcal{S}}(q_{\mathcal{S}})q_{\mathcal{S}}] \\
\text{s.t.} \quad & \mathbb{E}[\theta_{\mathcal{S}}(q_{\mathcal{S}})]\le(\lambda_C+\lambda_L)/\eta \\
& \lambda_L/\eta\le\theta_{\mathcal{S}}(q_{\mathcal{S}})\le\hat{\lambda}_{\mathcal{N}}, \qquad \forall q_{\mathcal{S}}\in\mathcal{Q}_{\mathcal{S}},
\end{aligned}$$

where $\theta_{\mathcal{S}}(q_{\mathcal{S}})$ denotes the dual variable, which depends on random demand $q_{\mathcal{S}}$, and $\mathcal{Q}_{\mathcal{S}}\subseteq\mathbb{R}$ is the support of random demand $q_{\mathcal{S}}$. The first constraint indicates that the expected value of $\theta_{\mathcal{S}}(q_{\mathcal{S}})$ cannot exceed the sum of the amortized storage cost and the off-peak price of adding one unit of capacity (adjusted for efficiency η). The second constraint specifies that the marginal cost of meeting demand can neither fall below λ_L/η nor exceed the exogenous crowdsourcing price $\hat{\lambda}_{\mathcal{N}}$ used in the auxiliary game.

Proof of Theorem 5. To show that $\boldsymbol{\beta}_L=(\beta_{i,L})_{i\in\mathcal{N}}$ is in the core if $\hat{\lambda}_{\mathcal{N}}\le\hat{\lambda}_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$, we first show that $\boldsymbol{\beta}_L$ is the efficient allocation, and then show that $\boldsymbol{\beta}_L$ satisfies the property of coalition rationality under the sufficient condition in the following.

(1) $\sum_{i\in\mathcal{N}}\beta_{i,L}=V_L(\mathcal{N})$.

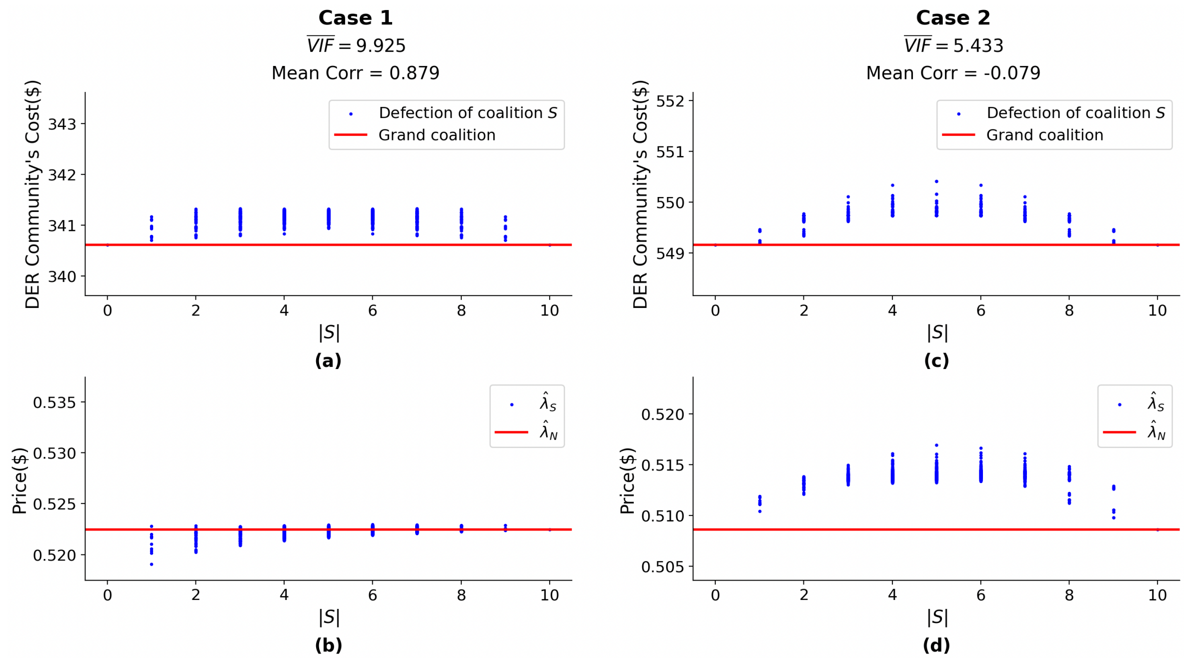
Because $\hat{V}_L(\mathcal{N})=V_L(\mathcal{N})$ and $\sum_{i\in\mathcal{N}}\beta_{i,L}=\hat{V}_L(\mathcal{N})$, $\boldsymbol{\beta}_L$ is an efficient allocation of the game $(\mathcal{N},V_L)$.

(2) $\sum_{i\in\mathcal{S}}\beta_{i,L}\le V_L(\mathcal{S})$ if $\hat{\lambda}_{\mathcal{N}}\le\hat{\lambda}_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$.

Because $\sum_{i\in\mathcal{S}}\beta_{i,L}\le\hat{V}_L(\mathcal{S})$ for any $\mathcal{S}\subseteq\mathcal{N}$, $\sum_{i\in\mathcal{S}}\beta_{i,L}\le V_L(\mathcal{S})$ if $\hat{V}_L(\mathcal{S})\le V_L(\mathcal{S})$ for any $\mathcal{S}\subseteq\mathcal{N}$. To prove $\hat{V}_L(\mathcal{S})\le V_L(\mathcal{S})$, we construct an auxiliary function with one decision variable x, one parameter $\hat{\lambda}$, and one random variable $q_{\mathcal{S}}$ as follows:

$$v(x,\hat{\lambda},q_{\mathcal{S}})\triangleq(\lambda_C+\lambda_L)x+\mathbb{E}[-\lambda_L(x-q_{\mathcal{S}}/\eta)^+ +\hat{\lambda}(q_{\mathcal{S}}-\eta x)^+],\quad \forall x\ge 0,\ \hat{\lambda}_{\mathcal{S}}\ge 0,\ q_{\mathcal{S}}\ge 0.$$

Figure B.1 **The Community's Expected Total Daily Cost and $\hat{\lambda}_{\mathcal{S}}$ at Different Sub-Coalition Size $|\mathcal{S}|$.**



For any given distribution of $q_{\mathcal{S}}$, define $x^*(\hat{\lambda})$ as the optimal solution of $\min_{x\geq 0} v(x,\hat{\lambda},q_{\mathcal{S}})$. If we substitute the optimal solution into $v(x,\hat{\lambda},q_{\mathcal{S}})$, we obtain a new function $V(\hat{\lambda},q_{\mathcal{S}}) \triangleq v(x^*(\hat{\lambda}),\hat{\lambda},q_{\mathcal{S}})$. The first-order derivative of $V(\hat{\lambda},q_{\mathcal{S}})$ with respect to $\hat{\lambda}$ is $\mathrm{d}V(\hat{\lambda},q_{\mathcal{S}})/\mathrm{d}\hat{\lambda} = \mathrm{d}v(x,\hat{\lambda},q_{\mathcal{S}})/\mathrm{d}\hat{\lambda}|_{x=x^*(\hat{\lambda})} = \mathbb{E}[(q_{\mathcal{S}} - \eta x^*(\hat{\lambda}))^+] \geq 0$. From the envelope theorem, $\mathrm{d}V(\hat{\lambda},q_{\mathcal{S}})/\mathrm{d}\hat{\lambda} \geq 0$ implies that $V(\hat{\lambda},q_{\mathcal{S}})$ is increasing in $\hat{\lambda}$.

By definition, because $V_L(\mathcal{S}) = \min_{c_i\geq 0, i\in\mathcal{S}}(\lambda_C + \lambda_L)\sum_{i\in\mathcal{S}} c_i + \mathbb{E}[-\lambda_L(\sum_{i\in\mathcal{S}} c_i - q_{\mathcal{S}}/\eta)^+ + \hat{\lambda}_{\mathcal{S}}(q_{\mathcal{S}} - \eta\sum_{i\in\mathcal{S}} c_i)^+]$ and $V(\hat{\lambda}_{\mathcal{S}},q_{\mathcal{S}}) = \min_{x\geq 0}(\lambda_C+\lambda_L)x + \mathbb{E}[-\lambda_L(x - q_{\mathcal{S}}/\eta)^+ + \hat{\lambda}_{\mathcal{S}}(q_{\mathcal{S}} - \eta x)^+]$, we have $V_L(\mathcal{S}) = V(\hat{\lambda}_{\mathcal{S}},q_{\mathcal{S}})$ for any $\mathcal{S}\subseteq\mathcal{N}$. Similarly, because $\hat{V}_L(\mathcal{S}) = \min_{c_i\geq 0,i\in\mathcal{S}}(\lambda_C+\lambda_L)\sum_{i\in\mathcal{S}} c_i + \mathbb{E}[-\lambda_L(\sum_{i\in\mathcal{S}} c_i - q_{\mathcal{S}}/\eta)^+ + \hat{\lambda}_{\mathcal{N}}(q_{\mathcal{S}} - \eta\sum_{i\in\mathcal{S}} c_i)^+]$ and $V(\hat{\lambda}_{\mathcal{N}},q_{\mathcal{S}}) = \min_{x\geq 0}(\lambda_C+\lambda_L)x + \mathbb{E}[-\lambda_L(x - q_{\mathcal{S}}/\eta)^+ + \hat{\lambda}_{\mathcal{N}}(q_{\mathcal{S}} - \eta x)^+]$, we obtain $\hat{V}_L(\mathcal{S}) = V(\hat{\lambda}_{\mathcal{N}},q_{\mathcal{S}})$ for any $\mathcal{S}\subseteq\mathcal{N}$. Because $V(\hat{\lambda},q_{\mathcal{S}})$ is increasing in $\hat{\lambda}$, it follows that $V(\hat{\lambda}_{\mathcal{N}},q_{\mathcal{S}}) \leq V(\hat{\lambda}_{\mathcal{S}},q_{\mathcal{S}})$ if $\hat{\lambda}_{\mathcal{N}} \leq \hat{\lambda}_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$. Consequently, it follows that $\hat{V}_L(\mathcal{S}) \leq V_L(\mathcal{S})$ if $\hat{\lambda}_{\mathcal{N}} \leq \hat{\lambda}_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$. We thus prove that $\sum_{i\in\mathcal{S}}\beta_{i,L} \leq V_L(\mathcal{S})$ if $\hat{\lambda}_{\mathcal{N}} \leq \hat{\lambda}_{\mathcal{S}}$ for any $\mathcal{S}\subseteq\mathcal{N}$. $\square$

Next, we empirically verify the sufficient condition, i.e., $\hat{\lambda}_{\mathcal{S}} \geq \hat{\lambda}_{\mathcal{N}}$, by analyzing a community in Austin, TX, with $|\mathcal{N}|$=10 residents from the Pecan Street project dataset (Pecan Street 2018). From the numerical results, we find that the validity of this condition is affected by the multicollinearity among demands of different consumers. We use average Variance Inflation Factor denoted by $\overline{VIF}$ and the mean correlation to assess demand correlation. A larger $\overline{VIF}$ value indicates the higher demand correlation among consumers. Specifically, $\overline{VIF} = \frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}}\frac{1}{1-R_i^2}$, where R_i^2 is the coefficient of determination (R-squared) of the regression of the i-th predictor on all the other predictors. The mean correlation is $\frac{2}{|\mathcal{N}|(|\mathcal{N}|-1)}\sum_{i<j}\rho_{ij}$, where ρ_{ij} is the Pearson correlation between the i-th and j-th variables.

As shown in Figure B.1, we compare the values of $\hat{\lambda}_{\mathcal{S}}$ at different coalition sizes $|\mathcal{S}|$ and the value of $\hat{\lambda}_{\mathcal{N}}$. Case 1 is an extreme scenario where consumers are selected so that their demands exhibit strong positive correlations. As shown in Figures B.1(a) and B.1(b), these correlations not only reduce the incentive to form a grand coalition but also invalidate our sufficient condition. In Case 2, demand profiles are regenerated so that demands between consumers still have significant correlations, but some of the correlations are negative. From Figures B.1(c) and B.1(d), we find that most values of $\hat{\lambda}_{\mathcal{S}}$ are larger than $\hat{\lambda}_{\mathcal{N}}$ when the advantage of forming the grand coalition is more prominent. Therefore, the numerical results show that this sufficient condition can be satisfied unless the correlation of consumer demands is excessively high.

Appendix C: The Joint Storage-Planning & Omni-Sharing Model With Season-Dependent TOU Tariffs

The joint storage-planning & omni-sharing model in Section 5.4 omits the variations of electricity prices and peak/off-peak periods from season to season for clarity of exposition. However, in practice, both the electricity prices and time intervals of peak/off-peak periods in TOU tariffs vary across seasons (EPCOR 2013). In this appendix, we provide a joint storage-planning model under season-dependent TOU tariffs. Let $\mathcal{K} = \{1, ..., K\}$ represent the set of TOU tariffs for different seasons within a year. Here we use subscript k to indicate variables associated with season $k \in \mathcal{K}$. The peak and off-peak electricity prices in the TOU tariff k given by the power grid are denoted by $\lambda_{H,k}$ and $\lambda_{L,k}$, respectively. Different time intervals are reflected in different peak electricity demands. The community's peak electricity demand under the TOU tariff k is denoted by $q_{\mathcal{N},k}$ with the known distribution. Let $\boldsymbol{q}_{\mathcal{N}}$ be a vector composed of $q_{\mathcal{N},k}$ for all $k \in \mathcal{K}$. Let ξ_k be the proportion of time that the TOU tariff k is effective in a year, which satisfies $\sum_{k\in\mathcal{K}} \xi_k = 1$.

We first extend the joint storage-planning & P2P-sharing model to account for multiple seasons. According to Equation (7), we formulate the community's expected total daily cost of joint storage-planning & P2P sharing under season-dependent TOU tariffs as

$$\mathbb{E}[V_{P2P}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})] = \lambda_C c_{\mathcal{N}} + \sum_{k\in\mathcal{K}} \xi_k \mathbb{E}\Big[\lambda_{L,k} \min\{c_{\mathcal{N}}, q_{\mathcal{N},k}/\eta\} + \lambda_{H,k}(q_{\mathcal{N},k} - \eta c_{\mathcal{N}})^+\Big].$$

The community's optimal storage capacity is denoted by $c_{P2P}^{*SD}(\mathcal{N}) \triangleq \arg\min_{c_{\mathcal{N}}\geq 0} \mathbb{E}[V_{P2P}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})]$. Let $F_{\mathcal{N},k}(\cdot)$ be the cumulative distribution function of peak-period energy demand $q_{\mathcal{N},k}$. The optimal storage capacity $c_{P2P}^{*SD}(\mathcal{N})$ can be numerically solved from the first-order condition of $\mathbb{E}[V_{P2P}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})]$ with respect to $c_{\mathcal{N}}$ (due to its convexity), i.e., $\lambda_C = \sum_{k\in\mathcal{K}} \xi_k(\eta\lambda_{H,k} - \lambda_{L,k}) \cdot \big(1 - F_{\mathcal{N},k}(\eta c_{P2P}^{*SD}(\mathcal{N}))\big)$.

Next, we extend the community's expected total daily cost of joint storage-planning & omni-sharing sharing defined in Section 5.4 to that under season-dependent TOU tariffs as follows:

$$\begin{aligned}\mathbb{E}[V_{\mathcal{N}}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})] =& \lambda_C c_{\mathcal{N}} + \sum_{k\in\mathcal{K}} \xi_k \mathbb{E}\Big[\lambda_{L,k} \min\{c_{\mathcal{N}}, q_{\mathcal{N},k}/\eta\} + \lambda\big(h^*(b_{\mathcal{N},k}(c_{\mathcal{N}}))\big) h^*(b_{\mathcal{N},k}(c_{\mathcal{N}})) \\ &+ \lambda_{H,k}\big(b_{\mathcal{N},k}(c_{\mathcal{N}}) - h^*(b_{\mathcal{N},k}(c_{\mathcal{N}}))\big)\Big],\end{aligned}$$

where $b_{\mathcal{N},k}(c_{\mathcal{N}}) = (q_{\mathcal{N},k} - \eta c_{\mathcal{N}})^+$ represents the total residual demand of the community with storage capacity $c_{\mathcal{N}}$ after stationary storage sharing. The community's optimal storage capacity is denoted by $c^{*SD}(\mathcal{N}) \triangleq \arg\min_{c_{\mathcal{N}}\geq 0} \mathbb{E}[V_{\mathcal{N}}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})]$. Similar to the proof process of Theorem 3, the first-order condition of $\mathbb{E}[V_{\mathcal{N}}^{SD}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})]$ with respect to $c_{\mathcal{N}}$ is $\lambda_C = \sum_{k\in\mathcal{K}} \xi_k \Big(\eta\lambda_{H,k}\big(1 - F_{\mathcal{N},k}(\eta c_{\mathcal{N}} + \overline{h}_k)\big) - \eta\lambda_{E,k}(\eta c_{\mathcal{N}})\big(F_{\mathcal{N},k}(\eta c_{\mathcal{N}} + \overline{h}_k) - F_{\mathcal{N},k}(\eta c_{\mathcal{N}})\big) - \lambda_{L,k}\big(1 - F_{\mathcal{N},k}(\eta c_{\mathcal{N}})\big)\Big)$, where $\lambda_{E,k}(x) = \mathbb{E}_k[\mathrm{d}(\lambda(h)h)/\mathrm{d}h|_{h=q_{\mathcal{N},k}-x} | 0 < h \leq \overline{h}_k]$ represents the expected marginal payment from the community with storage capacity x to CSEVs under TOU tariff k; $\overline{h}_k$ represents the maximum amount of energy that the community is willing to crowdsource from CSEVs in TOU tariff k, determined by the condition $\mathrm{d}(\lambda(h)h)/\mathrm{d}h = \lambda_{H,k}$. One can numerically solve this first-order condition for the optimal storage capacity (due to its convexity). After optimizing the capacity of the community, we can use a stochastic programming duality approach proposed in Section 5.4 to allocate cost. To sum up, we extend our joint storage-planning model by considering season-dependent TOU tariffs.

Appendix D: Summary of Notation

Table D.1: Notation

Symbol	Description
Sets	
$\mathcal{N}$	Set of all consumers in the community
$\mathcal{S}$	Subset of consumers in the community, $\mathcal{S} \subseteq \mathcal{N}$
$\{\mathcal{S}_1, ..., \mathcal{S}_K\}$	Optimal coalition structure of consumers who are not in $\mathcal{S}$
$\{R, P\}$	Set of CSEV types, where R represents ride-sharing EVs and P represents private-use EVs
$Q_{\mathcal{S}}$	Support of random demand $q_{\mathcal{S}}$
$\mathcal{K}$	Set of TOU tariffs for different seasons within a year
Vectors	
$\boldsymbol{\beta}_R$	Cost allocation vector of the storage-present & omni-sharing cooperative game
$\boldsymbol{\beta}_L$	Cost allocation vector of the joint storage-planning & omni-sharing cooperative game
$\boldsymbol{q}_{\mathcal{N}}$	Vector composed of $q_{\mathcal{N},k}$ for all $k \in \mathcal{K}$
Parameters	
λ_C	Amortized storage cost per kWh, \$/kWh
λ_L	Off-peak electricity price given by the power grid, \$/kWh
λ_H	Peak electricity price given by the power grid, \$/kWh
λ_X	Maximum unit purchase price of electricity (among all entities except the community) offered to CSEVs, \$/kWh
η_c	Coefficient of charge efficiency
η_d	Coefficient of discharge efficiency
η	Coefficient of charge and discharge round-trip efficiency
η_l	Electricity line loss rate per mile, mile^{-1}
$\underline{e}$, $\overline{e}$	Minimum and maximum safe SOC bounds for CSEV batteries, respectively, kWh
m	CSEV type index
ϱ	Network utilization rate per kWh per mile, \$/(kWh·mile)
δ	Coefficient of capacity loss induced by discharge in energy sharing relative to discharge in driving for CSEVs
g	Average battery degradation cost per unit of energy charged or discharged, \$/kWh
π_m	Threshold value for a type-m CSEV with full energy, exceeding its expected outside option, \$
ω_m	Type-m CSEV marginal value diminishing rate
$\underline{\lambda}$, $\overline{\lambda}$	Lower and upper bounds of the uniform price range, \$
$\overline{h}$	Maximum amount of energy that the community is willing to crowdsource from CSEVs, kWh
c_i	Storage capacity of consumer i in the storage-present scenario, kWh
$c_{\mathcal{S}}$	Sum of storage capacities of consumers in set $\mathcal{S}$, kWh
γ	Critical fractile ratio
$\hat{\lambda}_{\mathcal{S}}$	Value of peak-period average energy payment price when the storage capacity is at its optimal value, \$/kWh
k	Seasonal index of the TOU tariff
$\lambda_{L,k}$	Off-peak electricity price in TOU tariff k given by the power grid, \$/kWh
$\lambda_{H,k}$	Peak electricity price in TOU tariff k given by the power grid, \$/kWh
ξ_k	Proportion of time that TOU tariff k is effective in a year
$\overline{h}_k$	Maximum amount of energy that the community is willing to crowdsource from CSEVs in TOU tariff k, kWh
Variables	
e	Available energy of a CSEV, kWh

Symbol	**Description (continued)**
r	Electrical distance from a CSEV to the community based on grid topology, mile
λ	Uniform price proposed by the community to crowdsource energy from CSEVs, $/kWh
h	Amount of energy crowdsourced by the community from CSEVs, kWh
b	Residual demand of the community after stationary storage sharing, kWh
q_i	Daily peak-period energy demand of consumer i, kWh
$q_{\mathcal{S}}$	Total daily peak-period energy demand of consumers in set $\mathcal{S}$, kWh
$\beta_{i,R}^{P2P}$	Cost allocation for consumer i in the storage-present P2P-sharing game, $
$\beta_{i,R}$	Cost allocation for consumer i in the present-storage omni-sharing game, $
$\beta_{i,L}^{P2P}$	Cost allocation for consumer i in the joint storage-planning & P2P-sharing game, $
$\beta_{i,L}$	Cost allocation for consumer i in the joint storage-planning & omni-sharing game, $
$q_{\mathcal{N},k}$	Daily peak-period energy demand of the community under TOU tariff k, kWh
Functions	
$\Lambda_m(e,r)$	Adequate payment to crowdsource a type-m CSEV driver who has available energy e and is located at distance r from the community, $
$S(e,r)$	Spatial mismatch fee borne by a CSEV with available energy e located at distance r from the community, $
$C(e)$	Battery degradation cost incurred by a CSEV when available energy e, $
$\Pi_m(e)$	Outside-option value of a type-m CSEV driver with available energy e, $
$l(r)$	Energy sharing efficiency
$G(\lambda)$	Amount of energy that the community crowdsources from CSEVs at uniform price λ, kWh
$\hat{e}_m(r,\lambda)$	Discharge-down-to energy level for a type-m CSEV located r distance away and facing a uniform price λ, kWh
$\hat{r}_m(\overline{e}-\underline{e},\lambda)$	Maximum distance within which a type-m CSEV with the maximum available energy $\overline{e}-\underline{e}$ facing uniform price λ is willing to share energy, mile
$n_m(e,r)$	Density of type-m CSEV drivers who has available energy e and is located at distance r from the community
$\lambda(h)$	Uniform price at which the community crowdsources a quantity h of energy from CSEVs, $/kWh
$W(h,b)$	Total cost for the community to cover its residual demand b by crowdsourcing energy h from CSEVs, $
$\lambda^*(b)$	Optimal uniform price for a given residual demand b of the community, $/kWh
$h^*(b)$	Optimal amount of crowdsourced energy from CSEVs, kWh
$\widetilde{\lambda}(b)$	Average energy payment price for meeting the community's residual demand b, $/kWh
$V_{P2P}(c_{\mathcal{S}},q_{\mathcal{S}})$	Total daily cost of coalition $\mathcal{S}$ with storage capacity $c_{\mathcal{S}}$ and demand $q_{\mathcal{S}}$ under P2P sharing, $
$b_{\mathcal{S}}(c_{\mathcal{S}})$	Total residual demand of the community when the consumers in set $\mathcal{S}$ form a coalition with a combined storage capacity of $c_{\mathcal{S}}$, kWh
$V_{\mathcal{S}}(c_{\mathcal{S}},q_{\mathcal{S}})$	Total daily cost of coalition $\mathcal{S}$ with storage capacity $c_{\mathcal{S}}$ and demand $q_{\mathcal{S}}$ under omni-sharing, $
$V_R(\mathcal{S})$	Total daily cost of coalition $\mathcal{S}$ under omni-sharing, $
$\lambda_R(b)$	Storage-present omni-sharing market clearing price, $/kWh
$\lambda_R^{P2P}(b)$	Storage-present P2P-sharing market clearing price, $/kWh
$V_L(\mathcal{S})$	Minimum expected total daily cost of coalition $\mathcal{S}$ under omni-sharing, $
$c_{P2P}^*(\mathcal{S})$	Optimal storage capacity of coalition $\mathcal{S}$ under P2P-sharing, kWh
$c^*(\mathcal{S})$	Optimal storage capacity of coalition $\mathcal{S}$ under omni-sharing, kWh
$F_{\mathcal{S}}(\cdot)$	Cumulative distribution function of demand $q_{\mathcal{S}}$
$V_{P2P,R}(\mathcal{S})$	Total daily cost of coalition $\mathcal{S}$ under P2P-sharing, $
$V_{P2P,L}(\mathcal{S})$	Minimum expected total daily cost of coalition $\mathcal{S}$ under P2P-sharing, $
$\lambda_E(x)$	Expected marginal payment from the community to CSEVs when the community's storage capacity is x, $/kWh
$\Omega(\cdot)$	CSEV-inflated cumulative distribution function
$\lambda_W(x)$	Average payment price from the community to CSEVs when the community's storage capacity is x, $/kWh
$\lambda_{\mathcal{S}}(c)$	Peak-period average energy payment price $\widetilde{\lambda}(b_{\mathcal{S}}(c))$ under the demand distribution when consumers in set $\mathcal{S}$ form a sub-alliance in the joint storage-planning & omni-sharing game, $/kWh
$\hat{V}_L(\mathcal{S})$	Minimum expected total daily cost of coalition $\mathcal{S}$ in the auxiliary game, $
$\check{V}_L(\mathcal{S})$	Dual of $\hat{V}_L(\mathcal{S})$, $

Symbol	Description (continued)
$\theta_{\mathcal{S}}(q_{\mathcal{S}})$	Dual variable that depends on random demand $q_{\mathcal{S}}$, \$/kWh
$\theta^*_{\mathcal{S}}(q_{\mathcal{S}})$	Optimal dual solution of $\theta_{\mathcal{S}}(q_{\mathcal{S}})$, \$/kWh
$V^{SD}_{P2P}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})$	Total daily cost of joint storage-planning & P2P sharing for the community under season-dependent TOU tariffs, \$
$c^{*SD}_{P2P}(\mathcal{N})$	Optimal storage capacity of joint storage-planning & P2P sharing for the community under season-dependent TOU tariffs, kWh
$F_{\mathcal{N},k}(\cdot)$	Cumulative distribution function of peak-period energy demand $q_{\mathcal{N},k}$
$V^{SD}_{\mathcal{N}}(c_{\mathcal{N}}, \boldsymbol{q}_{\mathcal{N}})$	Total daily cost of joint storage-planning & omni-sharing for the community under season-dependent TOU tariffs, \$
$b_{\mathcal{N},k}(c_{\mathcal{N}})$	Total residual demand of the community with storage capacity $c_{\mathcal{N}}$, kWh
$c^{*SD}(\mathcal{N})$	Optimal storage capacity of joint storage-planning & omni-sharing for the community under season-dependent TOU tariffs, kWh
$\lambda_{E,k}(x)$	Expected marginal payment from the community with storage capacity x to CSEVs under TOU tariff k, \$/kWh

Appendix E: Data Description

Electricity Prices and Demand. The community's peak-period energy demand is estimated based on the historical data recorded every 15 minutes from 25 Texas residents in 2018 from the Pecan Street project (Pecan Street 2018). As shown in Table E.2, the baseline for peak and off-peak prices is set according to the TOU rates of Con Edison (2024), which is the primary electricity provider for the City of New York and its surrounding regions.

Table E.2 Time-of-use Rates of Con Edison

	Time-of-use periods	Peak prices	Off-peak prices	Price difference
Summer season	June 1 to Sept 30	\$0.3523/kWh	\$0.0249/kWh	\$0.3274/kWh
Non-summer season	All other months	\$0.1305/kWh	\$0.0249/kWh	\$0.1056/kWh

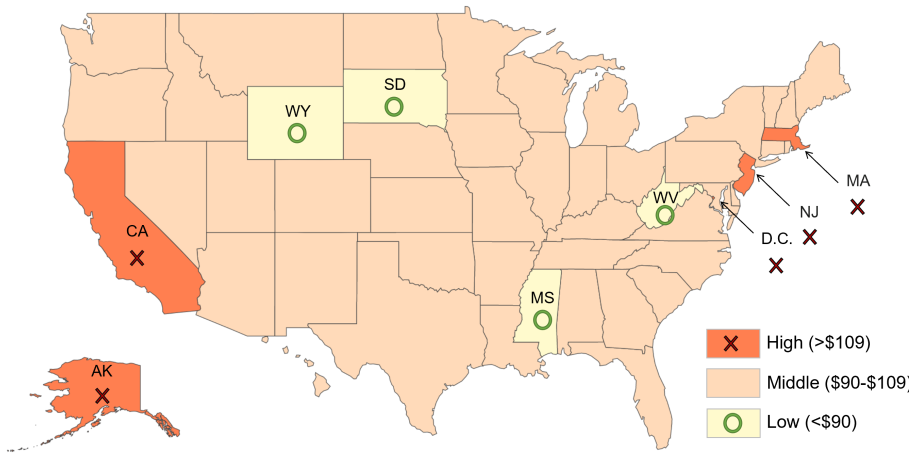
Available Energy. The maximum available energy of CSEVs is the difference between the battery capacity $\overline{e}$ and the minimum battery level of $\underline{e}$, i.e., $\overline{e} - \underline{e} = 54.56$ kWh: (1) the battery capacity $\overline{e} = 68.2$kWh is based on the Electric Vehicle Database (2023), and (2) the minimum battery level $\underline{e} = 13.64$ kWh is 20% of $\overline{e}$ as the undercharged level (Kahn and Lerner 2023). In addition, we set available energy e as a random variable uniformly distributed between $\underline{e}$ and $\overline{e}$.

Spatial Mismatch. Two parameter values about spatial mismatch are from literature and official websites: (1) The network utilization rate, $\varrho = \$2 \times 10^{-4}/(\text{kWh}\cdot\text{mile})$, is from DeSantis et al. (2021). (2) The coefficient of electrical line loss as $\eta_l = 3.22 \times 10^{-4}$ per mile is based on estimates in Rantaniemi et al. (2022).

Battery Degradation. Two parameters related to battery degradation are set as follows: According to Farzin et al. (2016), the average battery degradation cost is $g = \$2.25 \times 10^{-6}$ per unit depth of discharge, and the coefficient accounting for the higher capacity loss during operation in discharging mode than in driving mode is $\delta = 2.2$.

Ride-sharing Driver Income. By analyzing the data on driver income per day from Salary.com (2024), we find that Uber driver income varies widely across the United States, as shown in Figure E.2. Figure E.2 categorizes driver income into three tiers: high (exceeding \$109), middle (\$90 - \$109), and low (less than \$90). By leveraging the income data from Salary.com (2024), we can estimate the corresponding outside-option values for ride-sharing drivers. As

Figure E.2 Daily Income Levels of Uber Drivers in All States of the United States.



described in Section 4.1, the outside-option value represents the income a driver could potentially earn in alternative employment. We estimate the ride-sharing drivers' outside-option value under a full-charge state by applying a fixed ratio, e.g., 30% (Mishel 2018, O'Neal 2024), to the income data. Subsequently, we can derive the corresponding key parameter values for different income levels, such as π_R and ω_R. In our case studies, we set the values of the outside-option parameter of private-use drivers equal to those of ride-sharing drivers (private-use and ride-sharing drivers differ only in their quantities).

Density of CSEVs. Parameter values related to the density of CSEVs are generally estimates of the order of magnitude, since CSEVs have the potential to thrive in the coming years. In the computational studies, we assume that the available energy and space density for ride-sharing EVs are uniformly distributed. The density of CSEV drivers at a distance of r is the product of the number of CSEV drivers per square mile and the area of the circular ring with a radius of r. We obtain the number of CSEV drivers per square mile and the area of the circular ring with different radii as follows:

(1) To obtain the number of CSEV drivers per square mile, we simulate the variation in spatial density of ride-sharing EV drivers during the peak period using data from Uber and Lyft drivers (Kaggle 2018). Based on these data, we set the number of ride-sharing EV drivers per square mile to 200. It is difficult to predict the actual density of available private-use EV drivers. In reality, private-use EVs constitute the majority of CSEVs. We therefore set the number of private-use EV drivers to twice that of ride-sharing EV drivers, i.e., 400 per square mile.

(2) To calculate the area of each circular ring, we discretize the distance from ride-sharing EV drivers to the community into an equidistant sequence with K elements, i.e., $(r_1, ..., r_K)$. Here, $r_1 = 0$ and $r_K = \hat{r}_R(\overline{e} - \underline{e}, \lambda_H)$, where the largest function $\hat{r}_R(\cdot)$ is defined in Section 4.2. The area of the circular ring with radius r_k $(1 \leq k \leq K)$ is approximately $3.14 \times (r_{k+1}^2 - r_k^2)$, where 3.14 approximates π. For ease of calculation, we use r_K as the maximum value of the equidistant sequence when estimating the number of both ride-sharing and private-use EVs at different distances.

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