Cooperative Energy Management of HVAC via Transactive Energy

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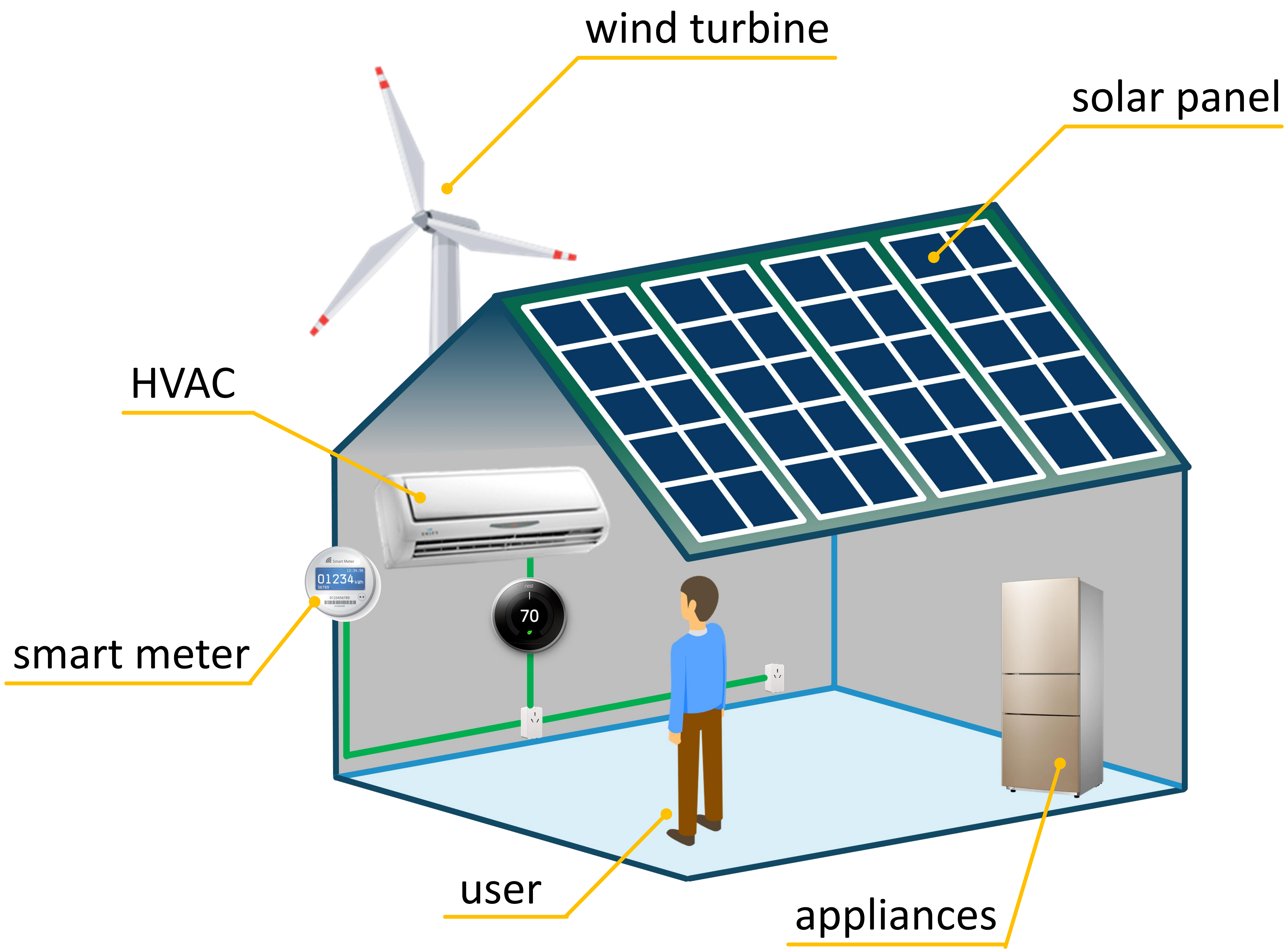
Outline

1. Background and challenges
2. System model
3. Problem formulation
4. Algorithm design
5. Simulation results
6. Conclusion and Q&A

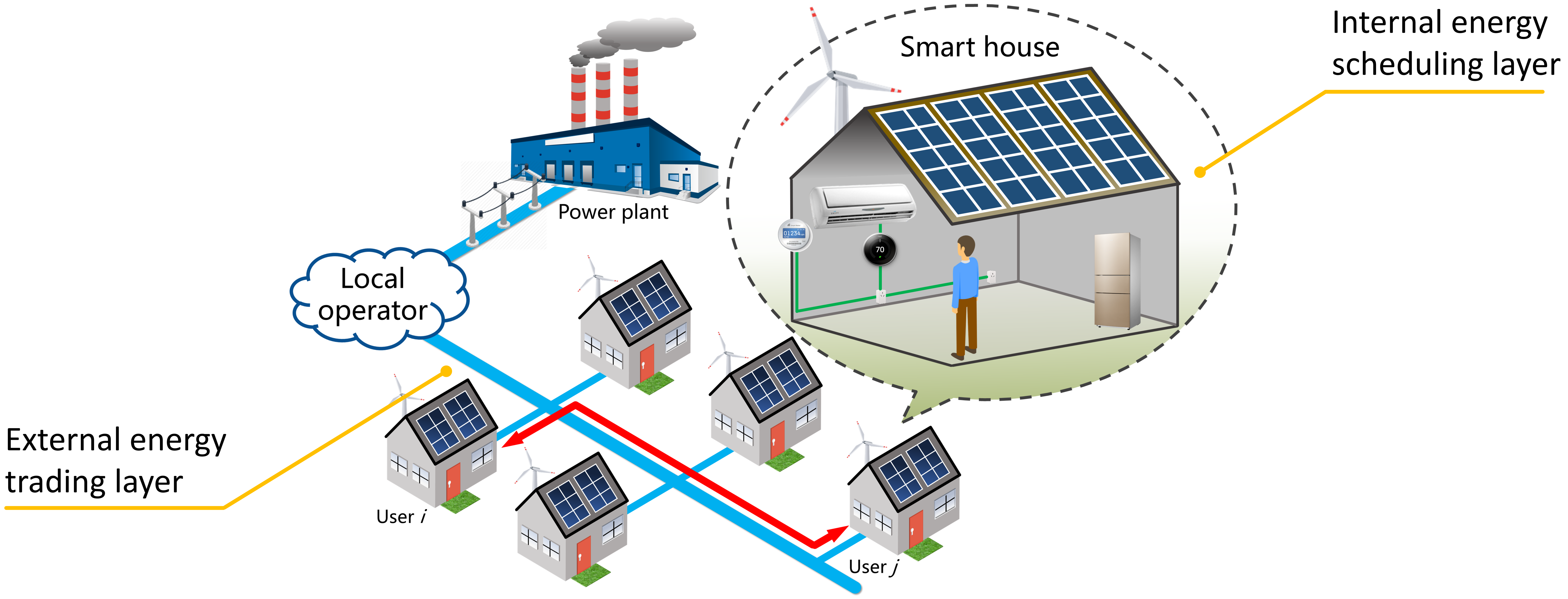
Heating ventilation and air conditioning (HVAC) in smart houses

- Smart house consists of
  1. Renewable energy generators
  2. HVAC system
  3. Other appliances
  4. Smart meter

- Challenges of HVAC management
  1. Power consumption is high
  2. Renewable energy is not fully utilized
  3. Privacy leakage



System model of the transactive energy platform



Multiple smart houses interconnected via the power grid

Set of users $\mathcal{N} = \{1, .., N\}$

Operational horizon $\mathcal{H} = \{1, ..., H\}$

Power supply model

- Renewable energy $p_i^{\mathrm{RE}}[t]$
- Grid supply $p_i^{\mathrm{G}}[t]$

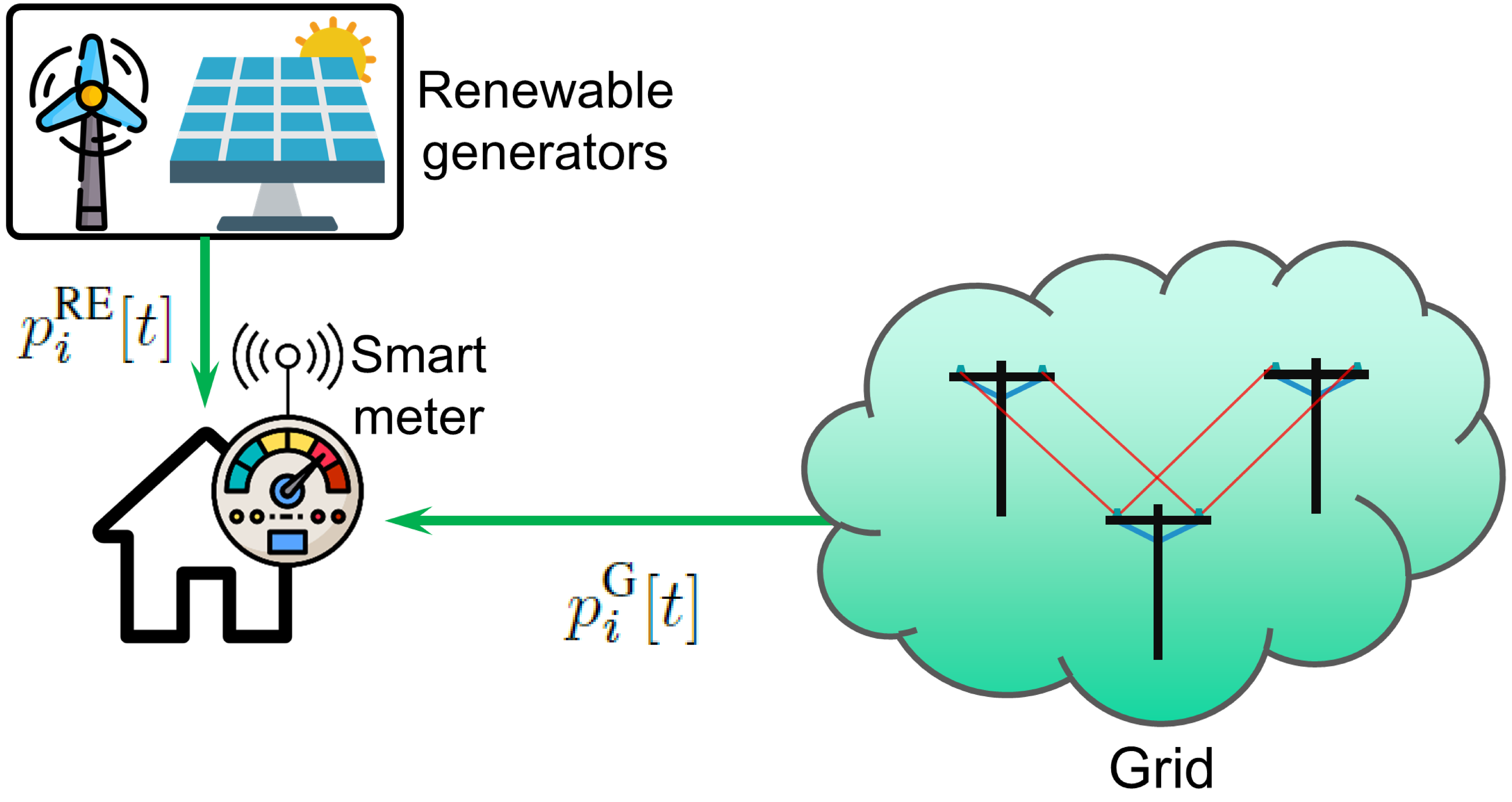
  with constraints

$$
\begin{aligned}
0 \le p_i^{\mathrm{RE}}[t] \le P_i^{\mathrm{RE}}[t],\ \forall i \in \mathcal{N}, t \in \mathcal{H},\\
0 \le p_i^{\mathrm{G}}[t] \le P_i^{\mathrm{G}},\ \forall i \in \mathcal{N}, t \in \mathcal{H},
\end{aligned}
$$

- Cost of the grid supply

$$C_i^{\mathrm{G}} = \pi_1^{\mathrm{G}} \sum\nolimits_{t \in \mathcal{H}} p_i^{\mathrm{G}}[t] + \pi_2^{\mathrm{G}} \max_{t \in \mathcal{H}} p_i^{\mathrm{G}}[t],$$

  two-part tariff billing is used



Load model

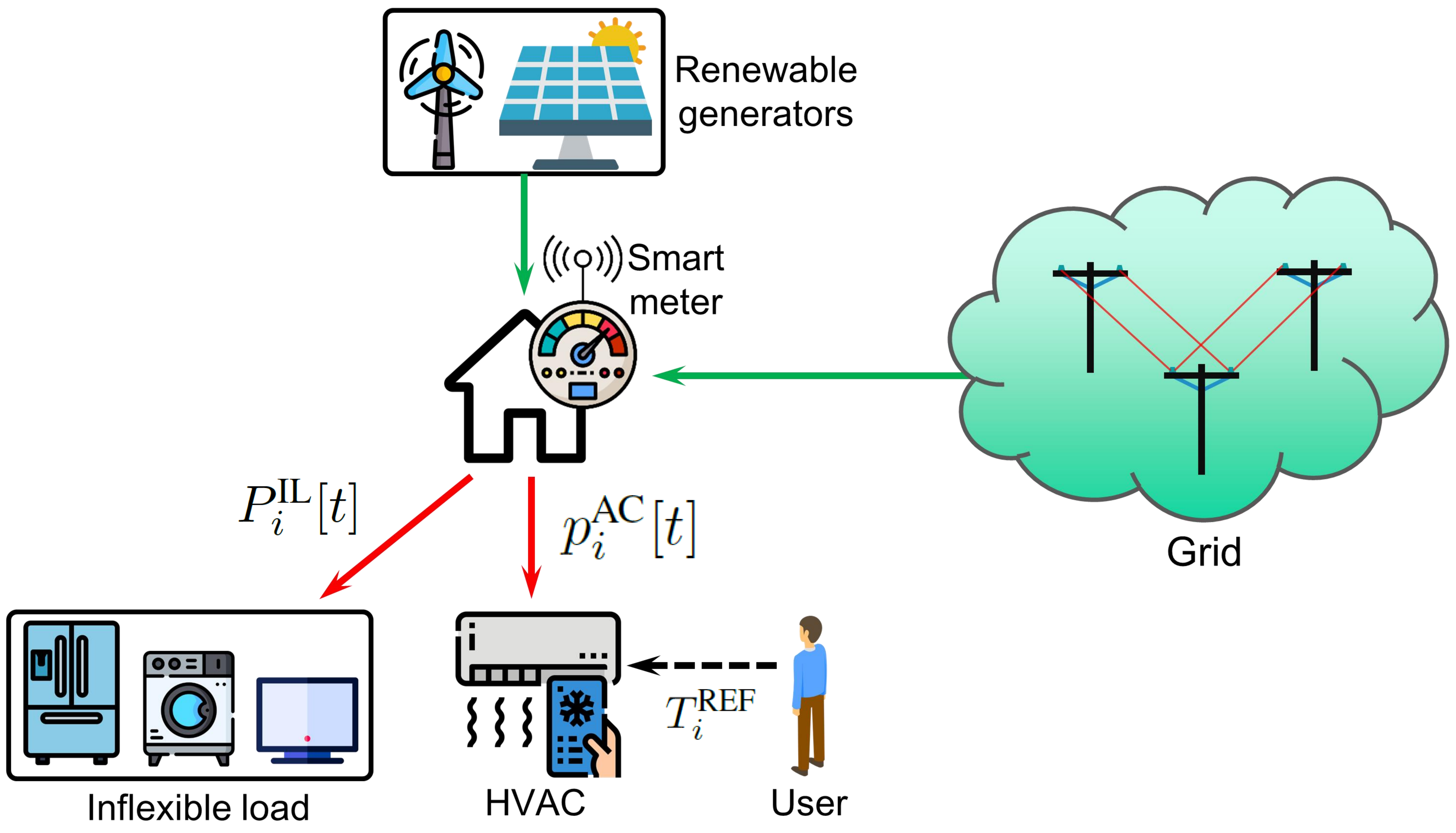
- Inflexible loads $P_i^{\mathrm{IL}}[t]$
- HVAC load $p_i^{\mathrm{AC}}[t]$
- Indoor temperature $T_i^{\mathrm{IN}}[t]$
- Outdoor temperature $T_i^{\mathrm{OUT}}[t]$
- User's preferred temperature T_i^{REF}

- Dynamics of the HVAC system

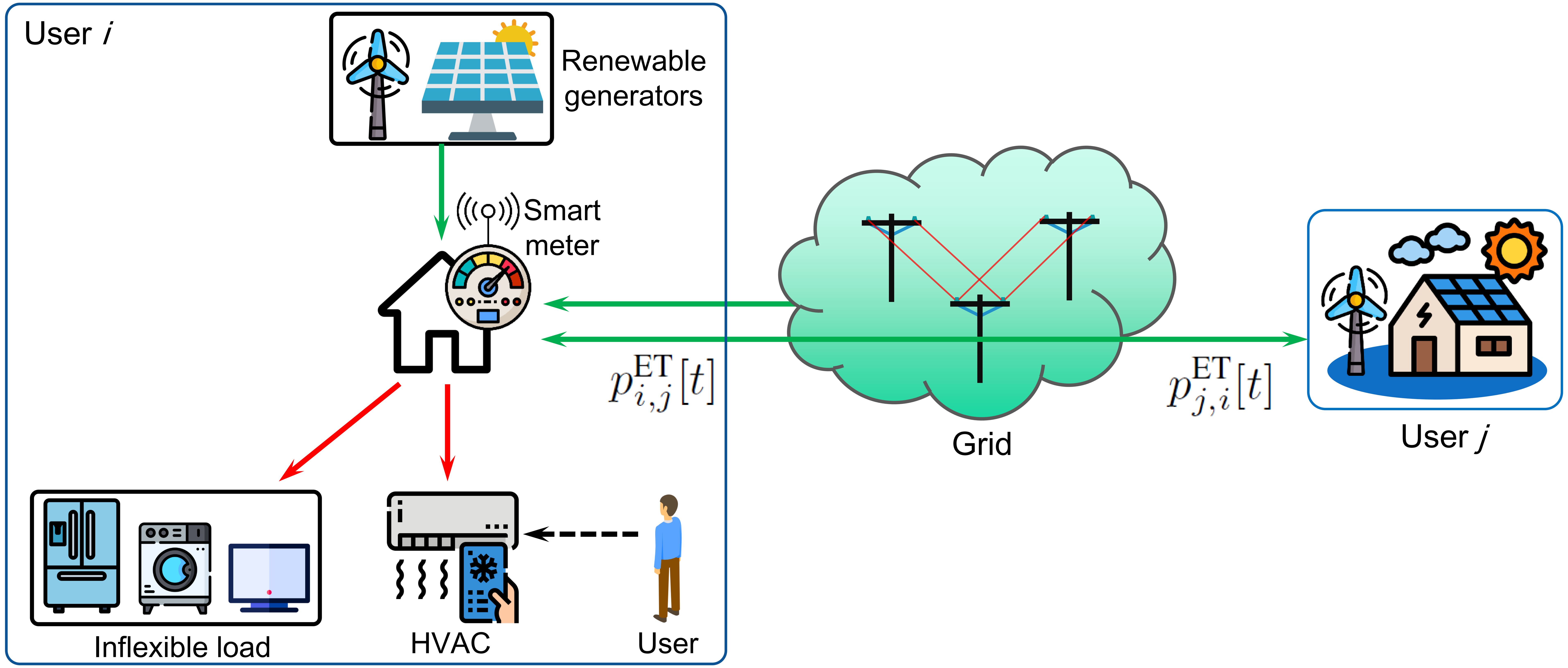
$$T_i^{\mathrm{IN}}[t] = T_i^{\mathrm{IN}}[t-1] - \frac{1}{C_i R_i}(T_i^{\mathrm{IN}}[t-1] - T_i^{\mathrm{OUT}}[t] + \eta_i R_i p_i^{\mathrm{AC}}[t]), \ \forall i \in \mathcal{N}, t \in \mathcal{H},$$

- Cost of the HVAC

$$C_i^{\mathrm{AC}} = \beta_i^{\mathrm{AC}} \sum_{t\in\mathcal{H}} \left(T_i^{\mathrm{IN}}[t] - T_i^{\mathrm{REF}}\right)^2, \ \forall i \in \mathcal{N}$$



Energy trading



$p_{i,j}^{\mathrm{ET}}[t]$ denotes the amount of electricity traded between user *i* and user *j* in time slot *t*

- Constraint $p_{i,j}^{\mathrm{ET}}[t] + p_{j,i}^{\mathrm{ET}}[t] = 0,\ \forall t \in \mathcal{H},\ \forall i \in \mathcal{N},\ \forall j \in \mathcal{N} \backslash i,$
- User's trading cost: $C_i^{\mathrm{ET}}(\boldsymbol{p}_i^{\mathrm{ET}}) = \sum_{t\in\mathcal{H}} \left(\pi[t] \sum_{j\in\mathcal{N}\backslash i} p_{i,j}^{\mathrm{ET}}[t] \right),$

Problem formulation

- Non-cooperative Scenario
- Users schedule their energy usages individually

Energy management problem:

User i's Energy Management Problem.

$$\begin{array}{ll} \min & C_i^{\mathrm{O}}(\boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}) \\ \text{subject to} & (1), (2), (4), (6), (8) \\ \text{variables:} & \{\boldsymbol{p}_i^{\mathrm{RE}}, \boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}\}. \end{array}$$

- Cooperative Scenario
- Users employ P2P energy trading

Cooperative energy management problem (CEMP)

CEMP: Cooperative Energy Management Problem

$$\begin{array}{ll} \min & \sum_{i \in \mathcal{N}} \left[C_i^{\mathrm{O}}(\boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}) + C_i^{\mathrm{ET}}(\boldsymbol{p}_i^{\mathrm{ET}})\right] \\ \text{subject to} & (1), (2), \ (4), \ (6), \ (7), \ (10) \\ \text{variables:} & \{\boldsymbol{p}_i^{\mathrm{RE}}, \boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}, \boldsymbol{p}_i^{\mathrm{ET}}, \ i \in \mathcal{N}\}. \end{array}$$

Overall cost is

$$C_i^{\mathrm{O}}(\boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}) \triangleq C_i^{\mathrm{G}}(\boldsymbol{p}_i^{\mathrm{G}}) + C_i^{\mathrm{AC}}(\boldsymbol{p}_i^{\mathrm{AC}})$$

Algorithm design

- Auxiliary variables $\hat{\boldsymbol{p}}_i^{\mathrm{ET}}$
- Dual variables $\boldsymbol{\lambda}$

$$\hat{p}_{i,j}^{\mathrm{ET}}[t] = p_{i,j}^{\mathrm{ET}}[t], \ \forall j \in \mathcal{N}\backslash i, \ \forall i \in \mathcal{N}, \ \forall t \in \mathcal{H},$$
$$\hat{p}_{i,j}^{\mathrm{ET}}[t] + \hat{p}_{j,i}^{\mathrm{ET}}[t] = 0, \ \forall j \in \mathcal{N}\backslash i, \ \forall i \in \mathcal{N}, \ \forall t \in \mathcal{H}.$$

- Augmented Lagrangian for Problem CEMP is

$$L = \sum_{i\in\mathcal{N}} \left[C_i^{\mathrm{O}}(\boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}) + C_i^{\mathrm{ET}}(\boldsymbol{p}_i^{\mathrm{ET}})\right] + \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{N}\backslash i} \sum_{t\in\mathcal{H}} \left[\frac{\rho}{2}\left(\hat{p}_{i,j}^{\mathrm{ET}}[t] - p_{i,j}^{\mathrm{ET}}[t]\right)^2 + \lambda_{i,j}[t](\hat{p}_{i,j}^{\mathrm{ET}}[t] - p_{i,j}^{\mathrm{ET}}[t])\right],$$

Distributed optimization method

- Lower-level problem

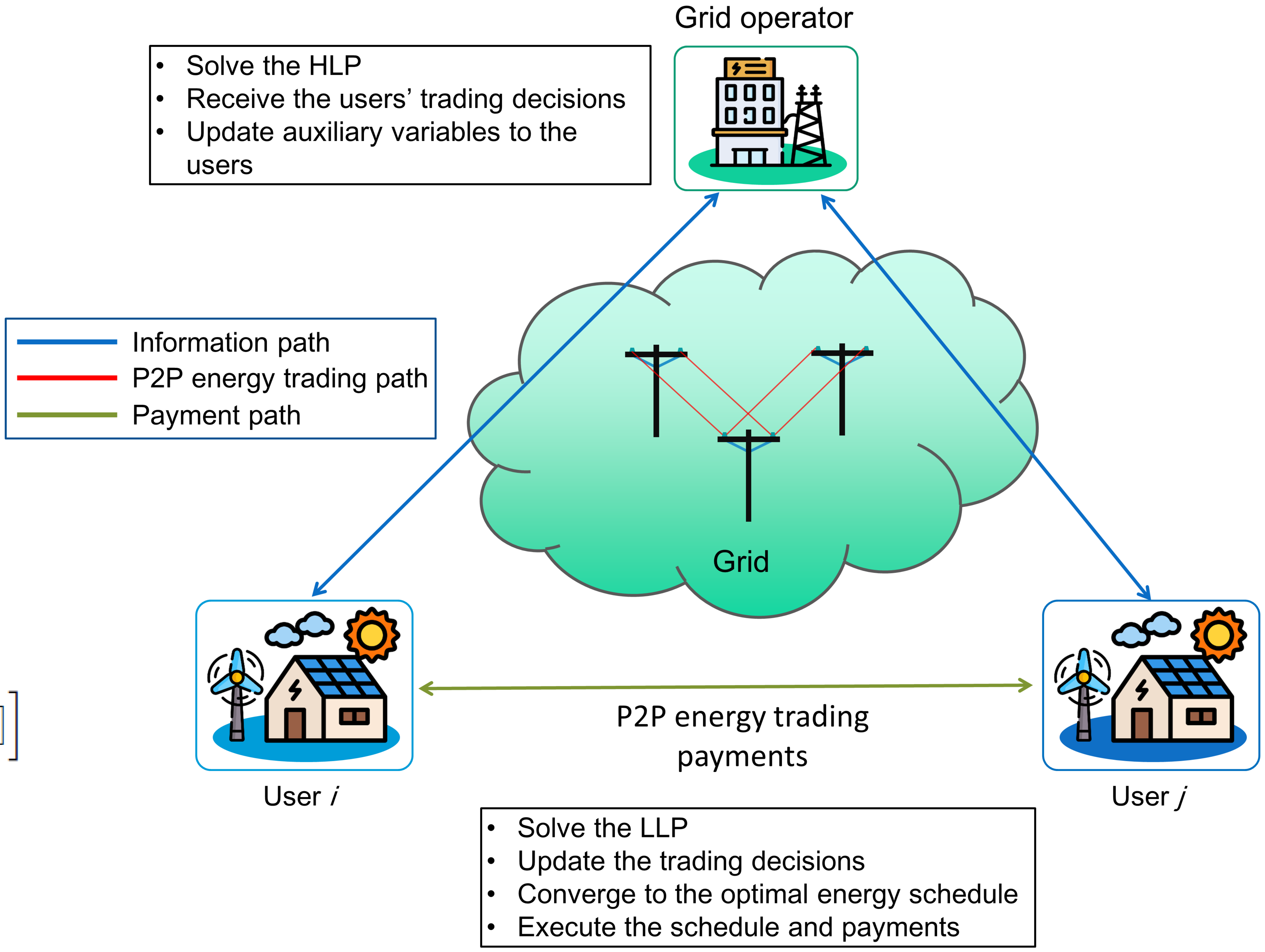
LLP1$_i$: Lower-level problem of **CEMP**.

$$\begin{aligned}
\min \quad & C_i^{\mathrm{O}}(\boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}) + C_i^{\mathrm{ET}}(\boldsymbol{p}_i^{\mathrm{ET}}) \\
& + \sum_{j \in \mathcal{N} \setminus i} \sum_{t \in \mathcal{H}} \left[\frac{\rho}{2} \left(\hat{p}_{i,j}^{\mathrm{ET}}[t] - p_{i,j}^{\mathrm{ET}}[t] \right)^2 - \lambda_{i,j}[t] p_{i,j}^{\mathrm{ET}}[t] \right] \\
\text{subject to} \quad & (1)-(2),\ (4),\ (6),\ (10) \\
\text{variables:} \quad & \{\boldsymbol{p}_i^{\mathrm{RE}}, \boldsymbol{p}_i^{\mathrm{G}}, \boldsymbol{p}_i^{\mathrm{AC}}, \boldsymbol{p}_i^{\mathrm{ET}}\}.
\end{aligned}$$

- higher-level problem

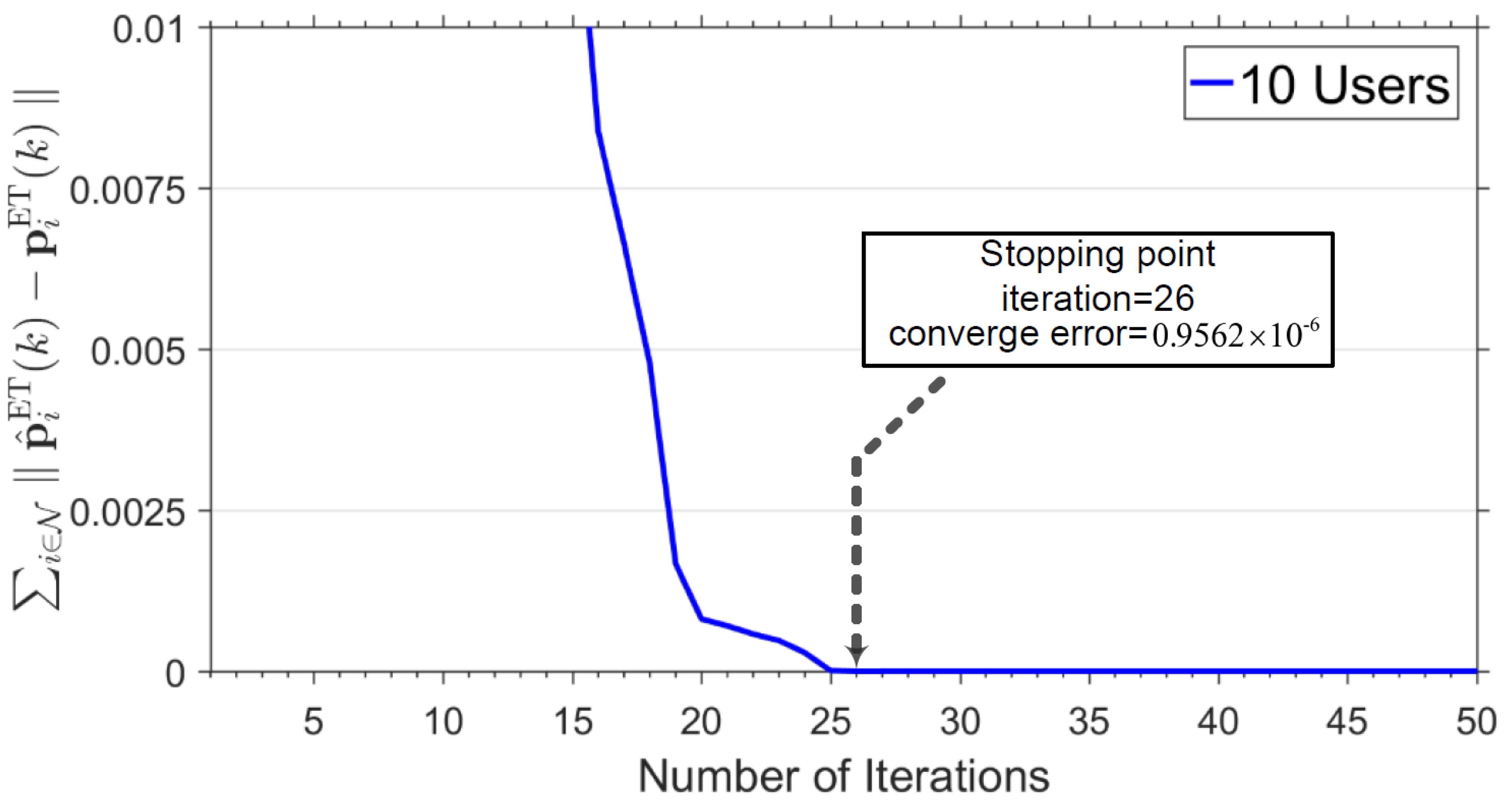
HLP1: higher-level problem of **CEMP**

$$\begin{aligned}
\min \quad & \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N} \setminus i} \sum_{t \in \mathcal{H}} \left[\frac{\rho}{2} \left(\hat{p}_{i,j}^{\mathrm{ET}}[t] - p_{i,j}^{\mathrm{ET}}[t] \right)^2 + \lambda_{i,j}[t] \hat{p}_{i,j}^{\mathrm{ET}}[t] \right] \\
\text{subject to} \quad & (13) \\
\text{variables:} \quad & \{\hat{\boldsymbol{p}}_i^{\mathrm{ET}},\ i \in \mathcal{N}\},
\end{aligned}$$

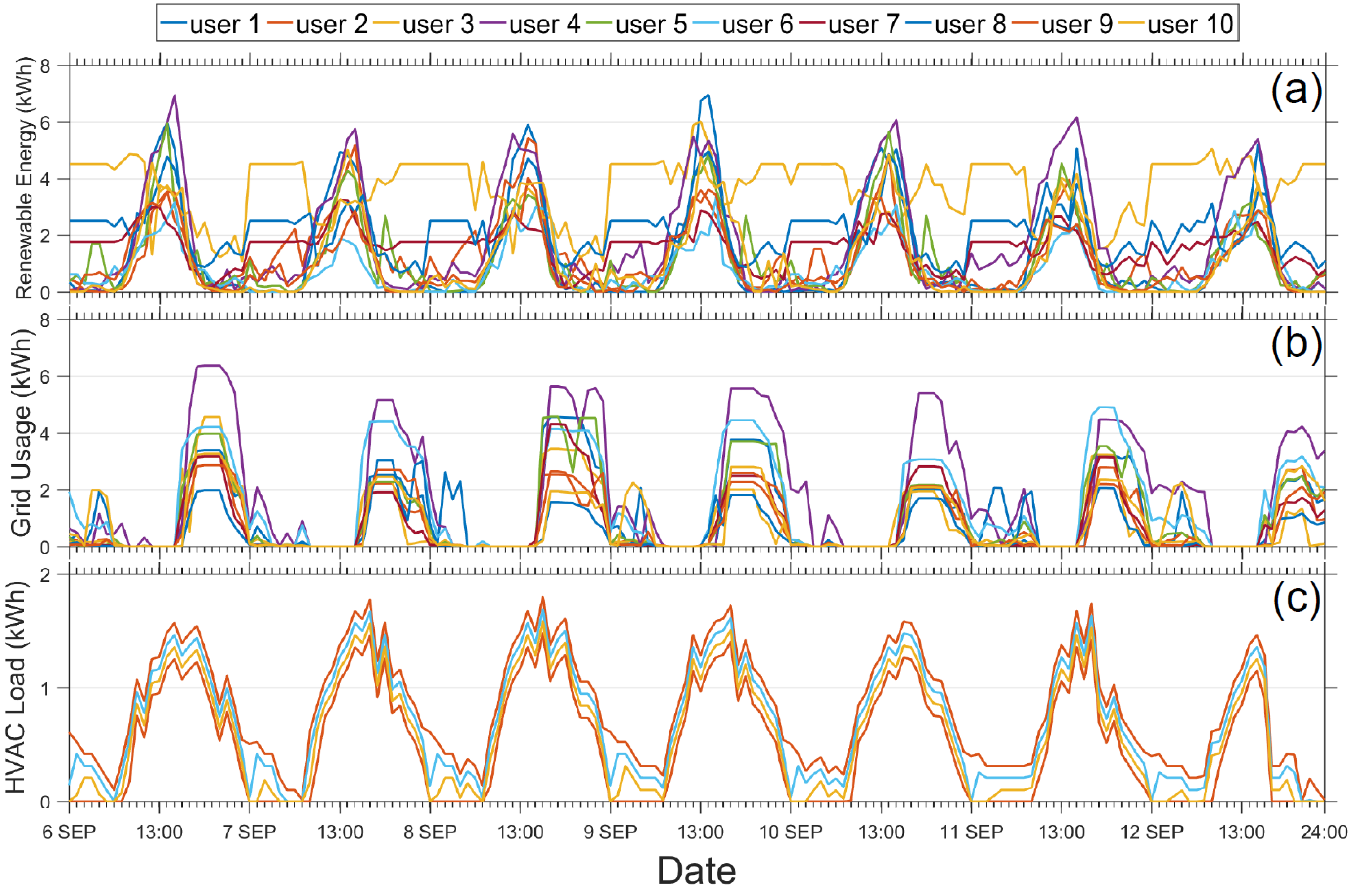


Simulation Results

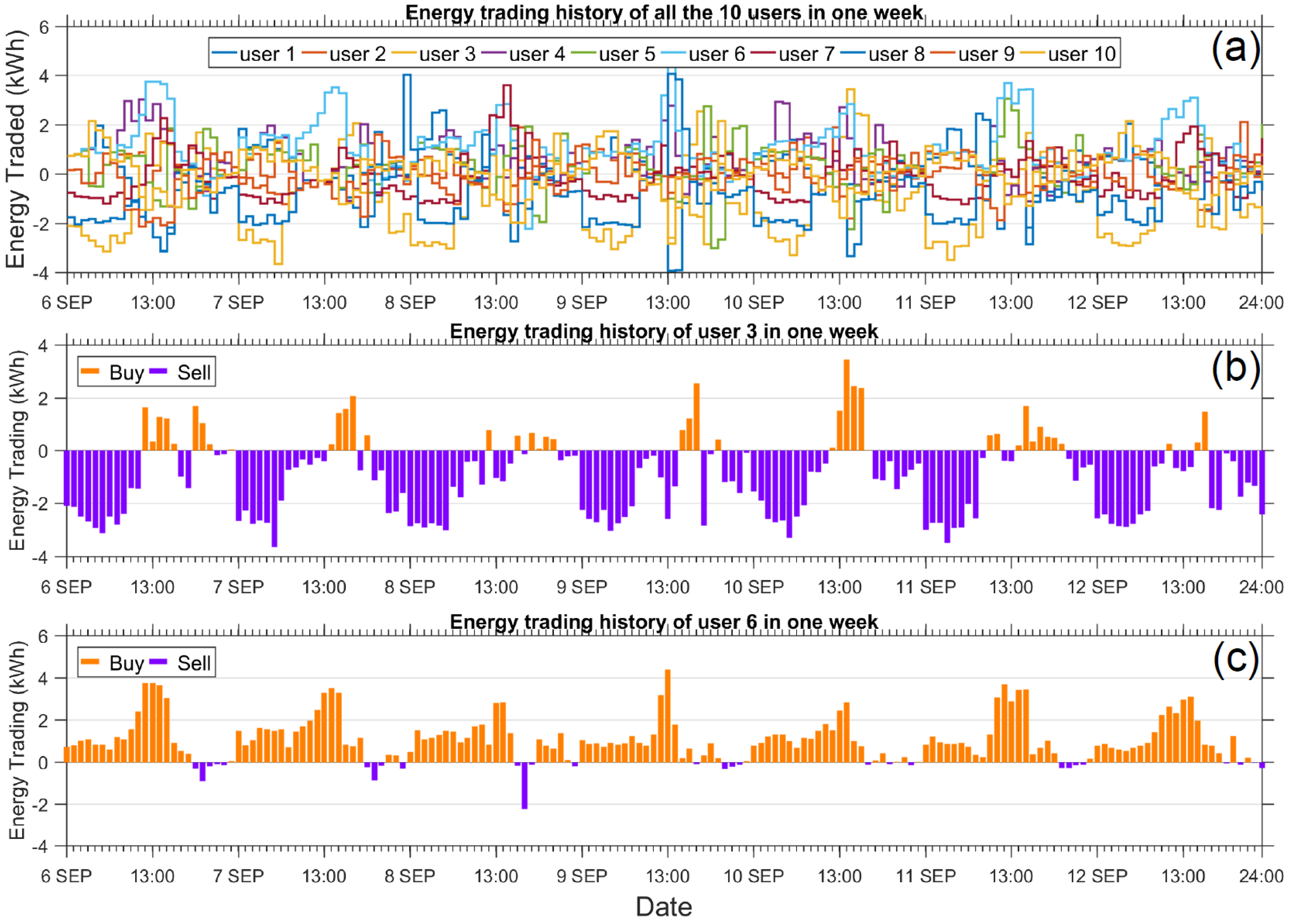
Convergence rate of the algorithm



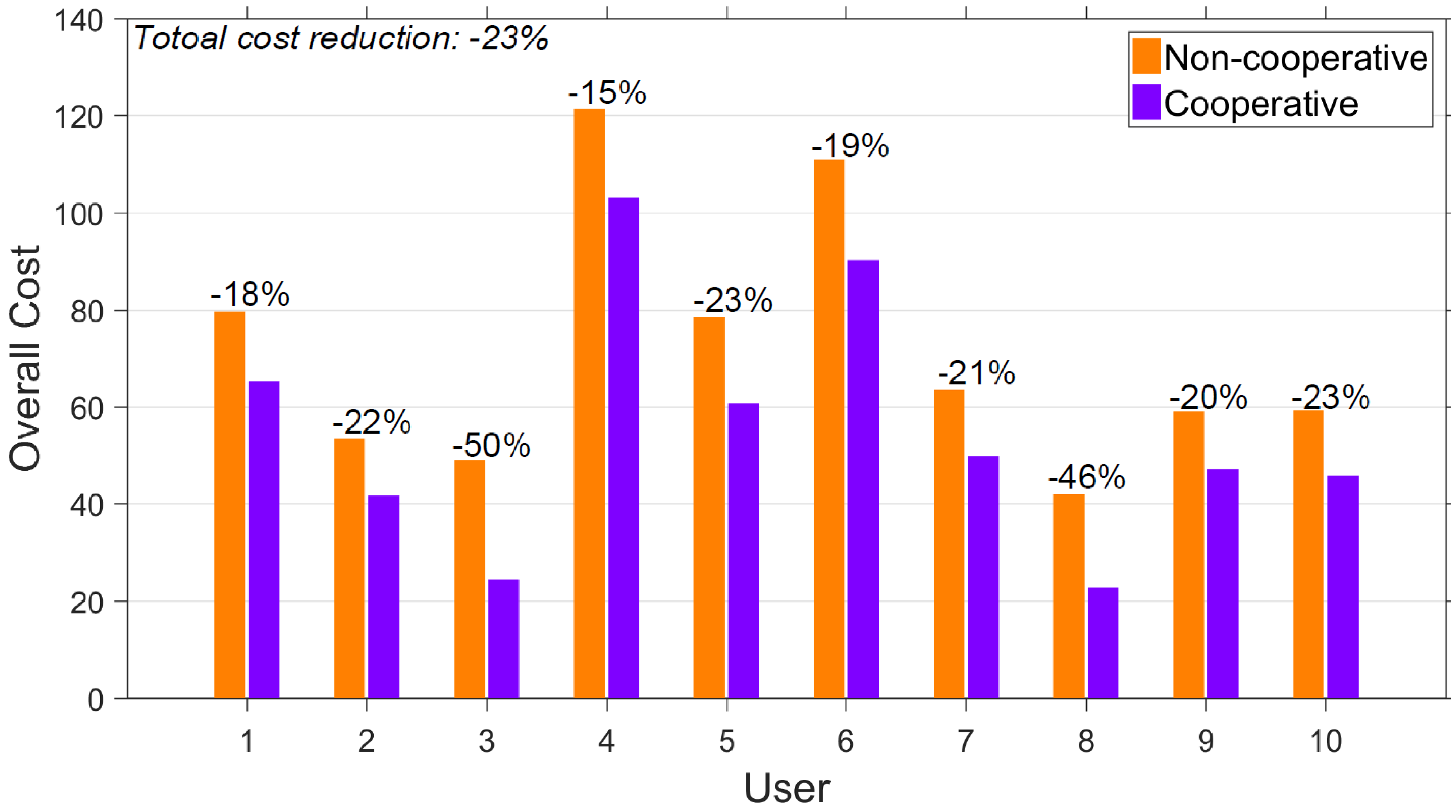
Energy scheduling results



P2P energy trading



Overall performance improvement



Conclusion

- A cooperative energy management platform to improve the efficiency of their HVAC energy management
- We designed a distributed energy trading algorithm that well preserves users' privacy and encourages users to trade energy to reduce energy costs.
- evaluated the distributed energy trading algorithm by extensive simulations
- reduced the system cost (defined as the overall cost of all the users) by 23%.

Thank you for your attendance!
Q&A