Blockchain for Transactive Energy Management of Distributed Energy Resources in Smart Grid


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Outline

1. Background
2. System Model and Problem Formulation
3. Algorithm Design
4. System Implementation and Evaluation
5. Summary

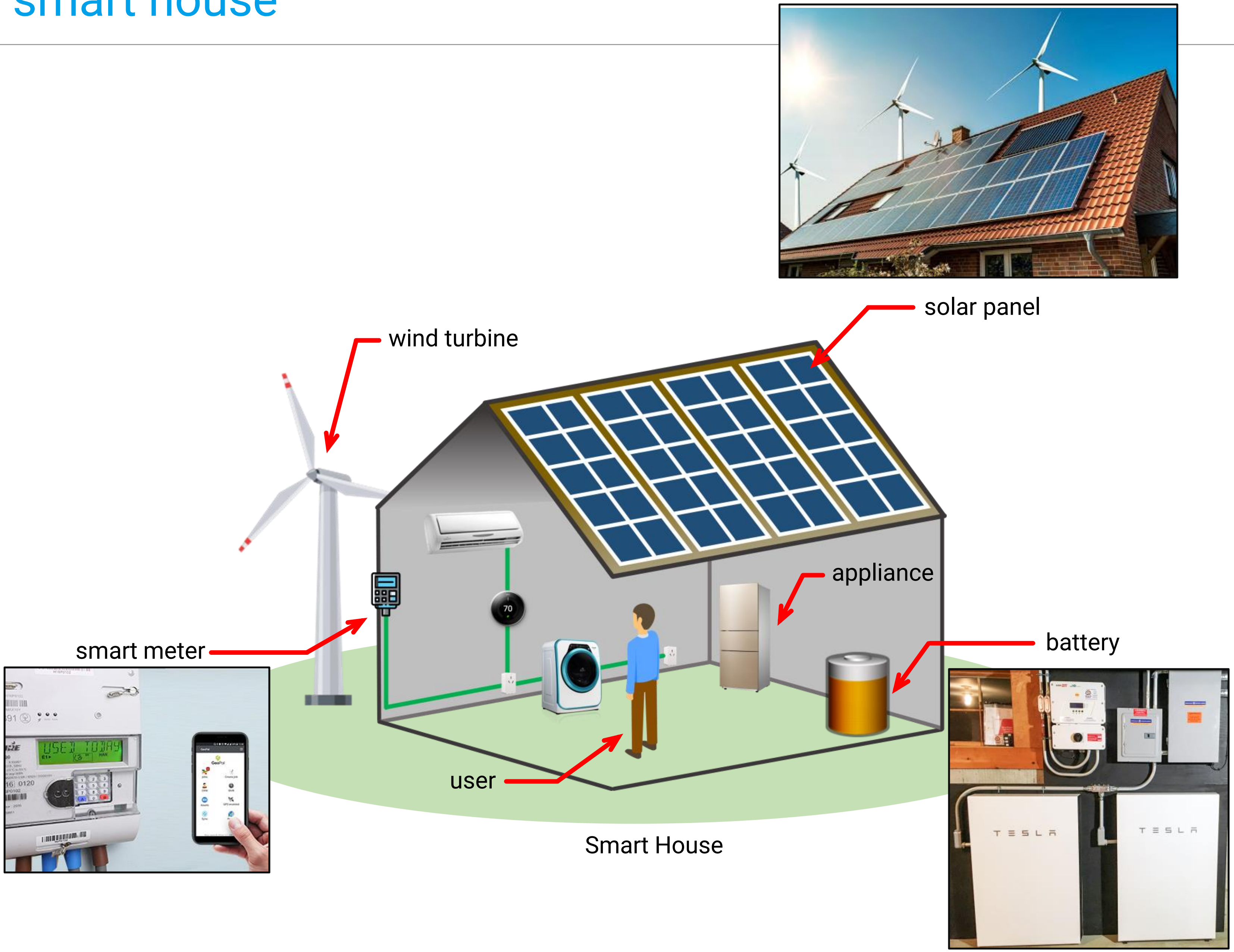
Distributed energy resources in smart house

Distributed energy resources (DERs) include:

- Renewable energy (RE) generators
- Electric appliances
- Battery energy storage system
- Smart meter

Challenges to current power system

- Complicated DER management algorithm
- Renewable energy is under-utilized
- Privacy leakage



Smart House

System model

Virtual power plant (VPP) scenario

Smart house is the prosumer in VPP

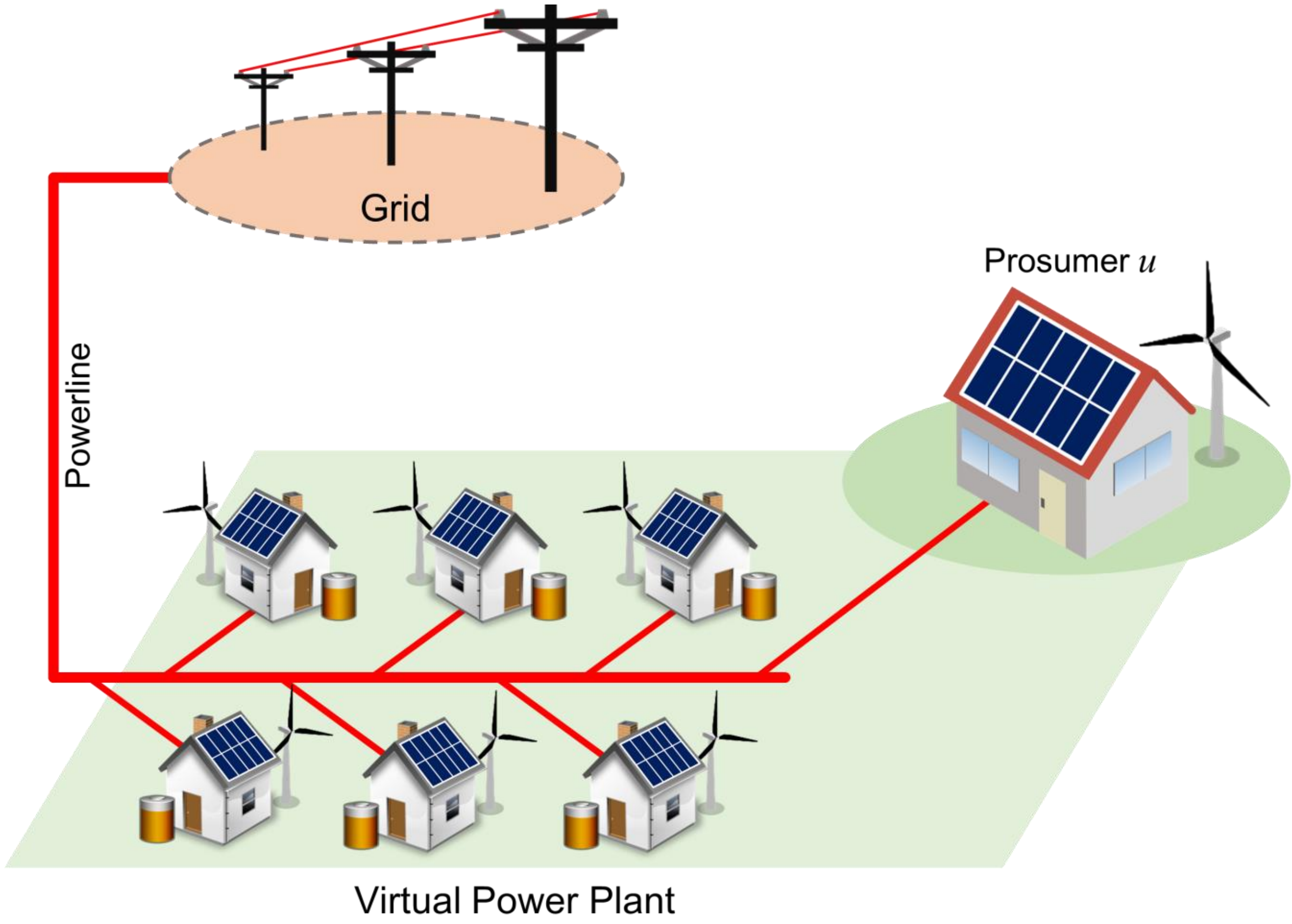
- Consume the electricity from the grid
- Produce electricity with RE

Set of prosumers

$$u \in \mathcal{U}=\{1,\ldots,U\}$$

Operational horizon (one-hour slot)

$$t \in \mathcal{H}=\{1,\ldots,24\}$$



Power supply

The power supply consist of two parts:

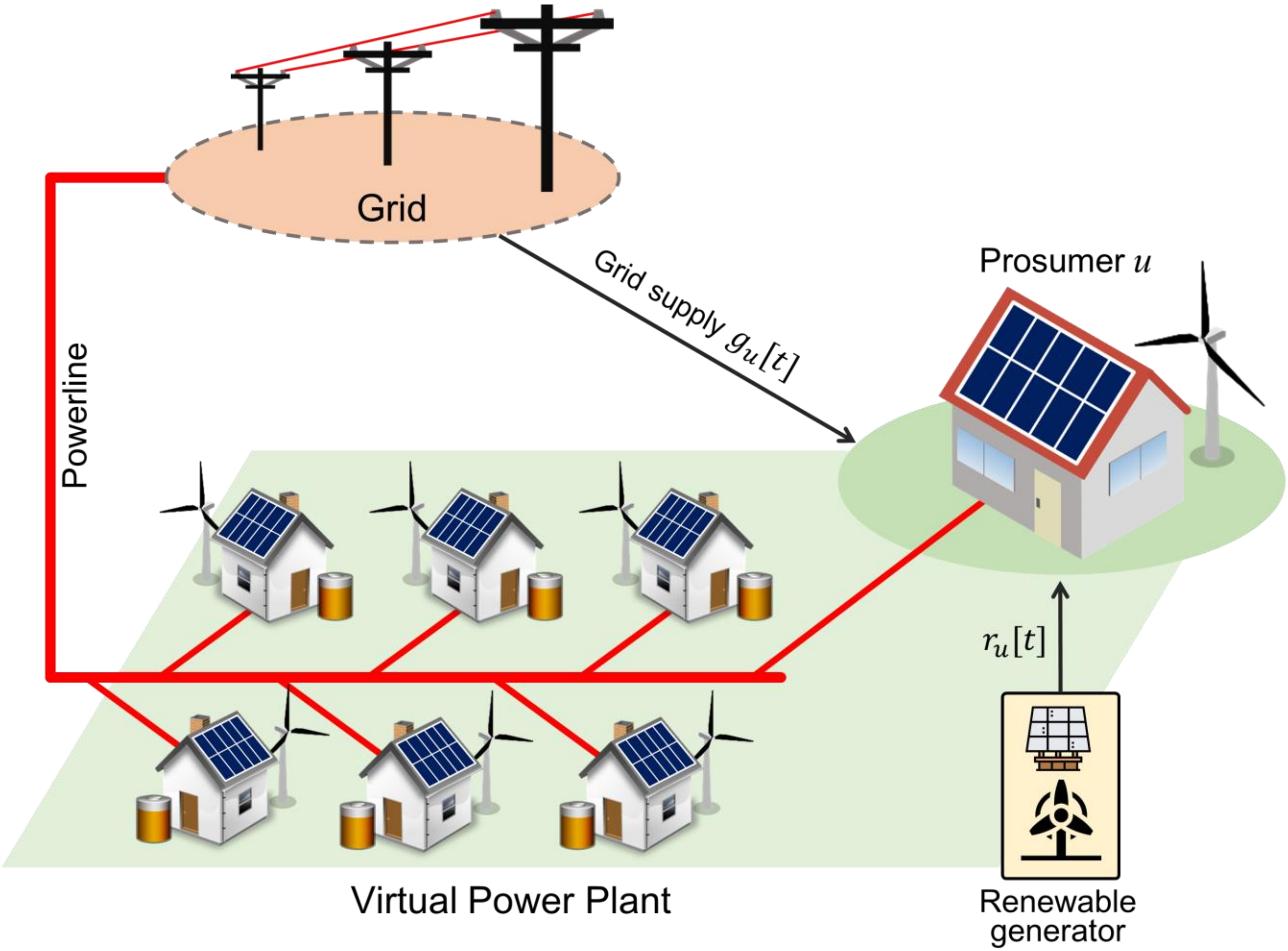
- Grid supply $g_u[t]$
- Renewable energy $r_u[t]$

Prosumer's cost of the grid supply

$$C_u^{\mathrm{G}} = \alpha \sum_{t\in\mathcal{H}} g_u[t] + \beta \max_{t\in\mathcal{H}} g_u[t]$$

with two-part tariff billing scheme

- normal price α
- peak price β



Electric appliance

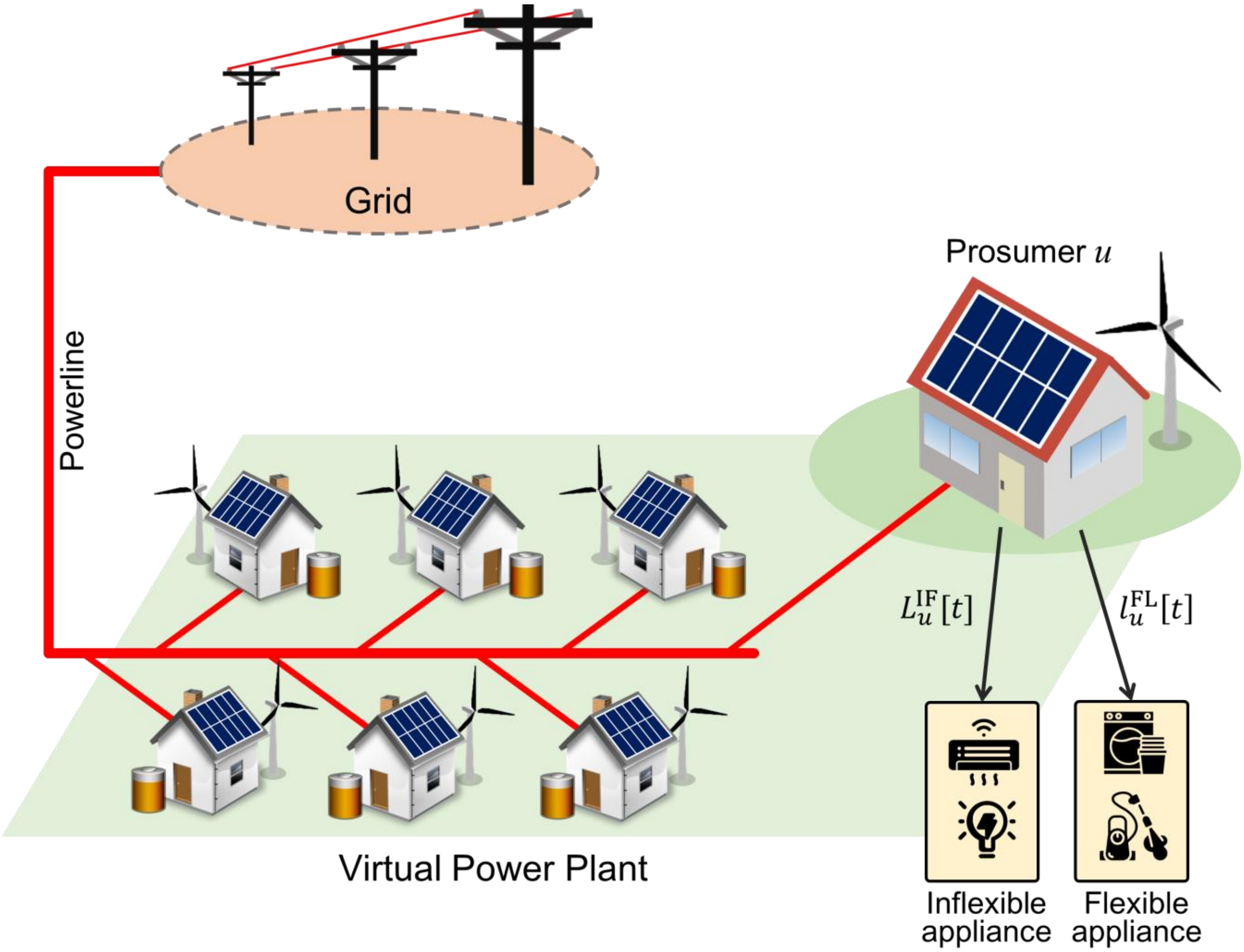
The appliances fall into two types:

- Flexible appliances $l_u^{FL}[t]$
  Time-shiftable loads: washer, dryer, …
- Inflexible appliances $L_u^{IF}[t]$
  Cannot be shifted: lighting, refrigerator, …

Prosumer's discomfort cost

$$C_u^{FL} = \sum_{t \in \mathcal{H}} (l_u^{FL}[t] - L_u^{Ref}[t])^2, \forall u \in \mathcal{U}$$

where the prosumer's preferred schedule is $L_u^{Ref}[t]$



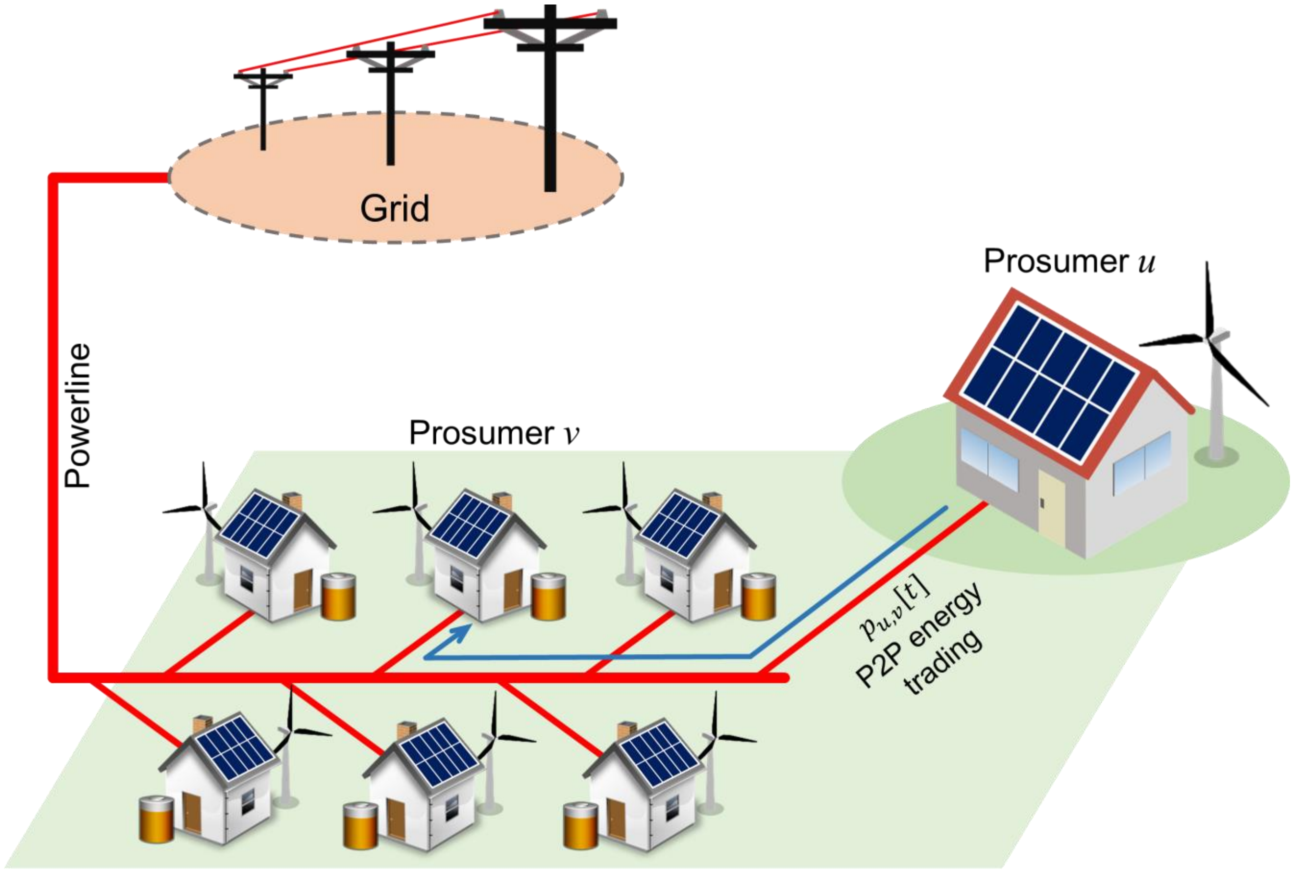
Peer-to-peer (P2P) energy trading

$p_{u,v}[t]$ denotes the amount of electricity that user *u* buys from user *v* in time slot *t*

Prosumer's trading cost:

$$C_u^{\mathrm{P2P}} = \sum_{t \in \mathcal{H}} \sum_{v \in \mathcal{U}} \pi^{\mathrm{P2P}} p_{u,v}[t]$$

where π^{P2P} is the price of P2P energy trading



Battery operation

The energy level of the prosumer's battery $b_u[t]$

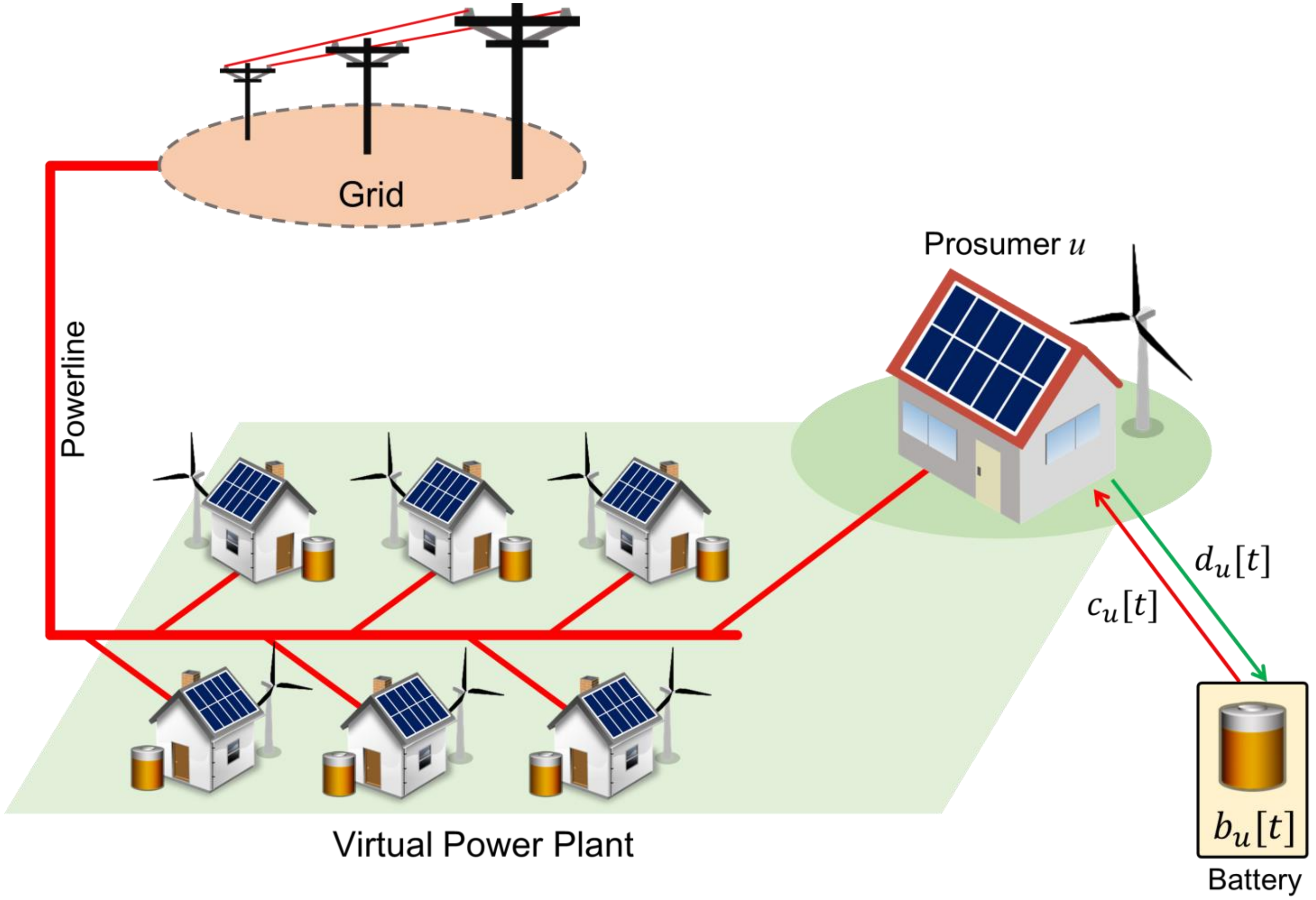
- Battery charging $c_u[t]$
- Battery discharging $d_u[t]$

The battery's operational dynamic:

$$b_u[t]=b_u[t-1]+\eta c_u[t]-\frac{d_u[t]}{\eta}$$

The prosumer's battery cost:

$$C_u^{\mathrm{BA}}=\sum_{t\in\mathcal{H}}\left(c_u[t]+d_u[t]\right)$$



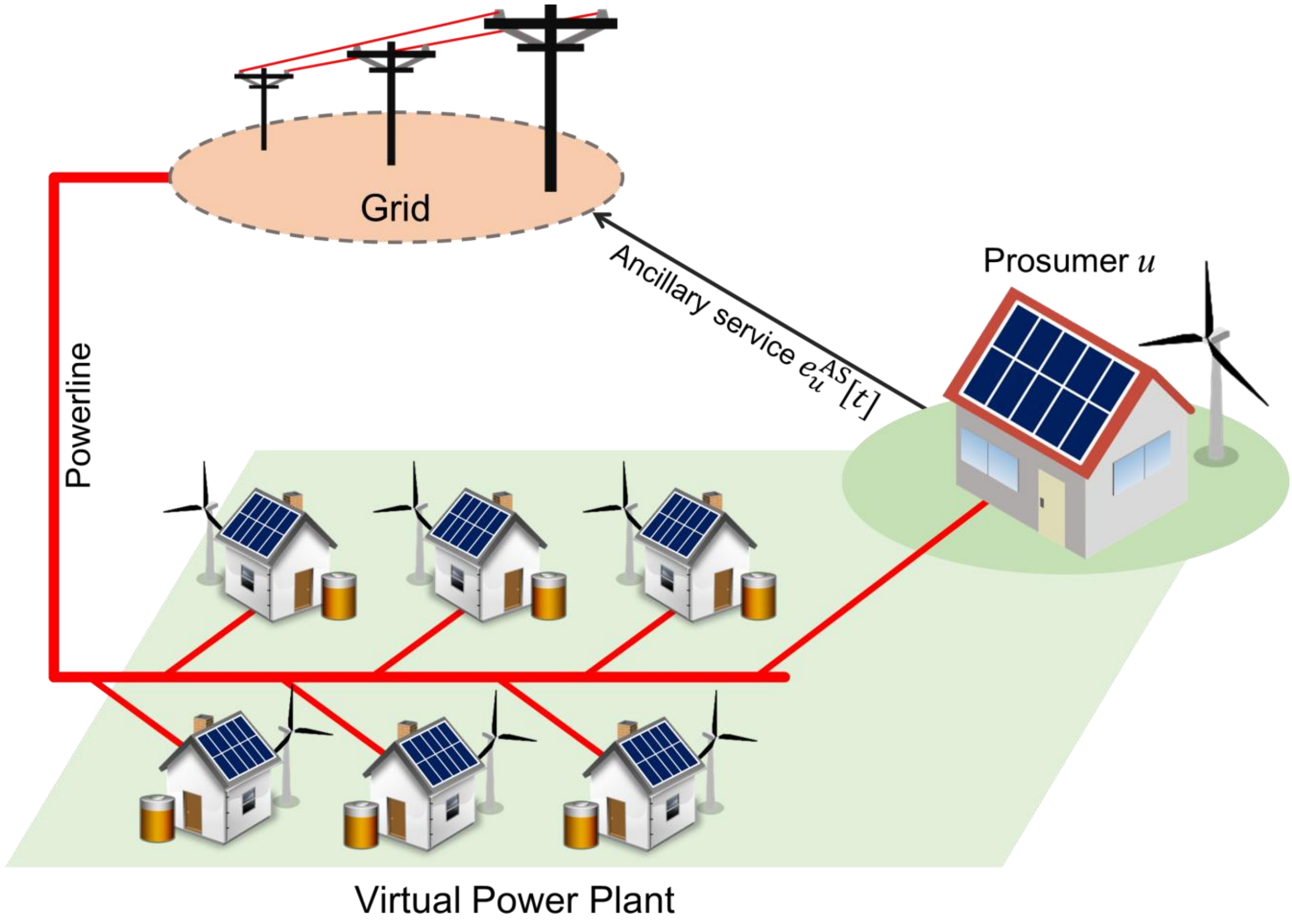
VPP ancillary service

$e_u^{\mathrm{AS}}[t]$ denotes the energy dispatched from the VPP to the grid

Prosumer's ancillary service reward

$$\mathcal{R}_u^{\mathrm{AS}} = \sum_{t\in\mathcal{H}} \pi^{\mathrm{AS}}[t] e_u^{\mathrm{AS}}[t]$$

$\pi^{\mathrm{AS}}[t]$ is the reward price



Problem formulation

Single prosumer's cost is

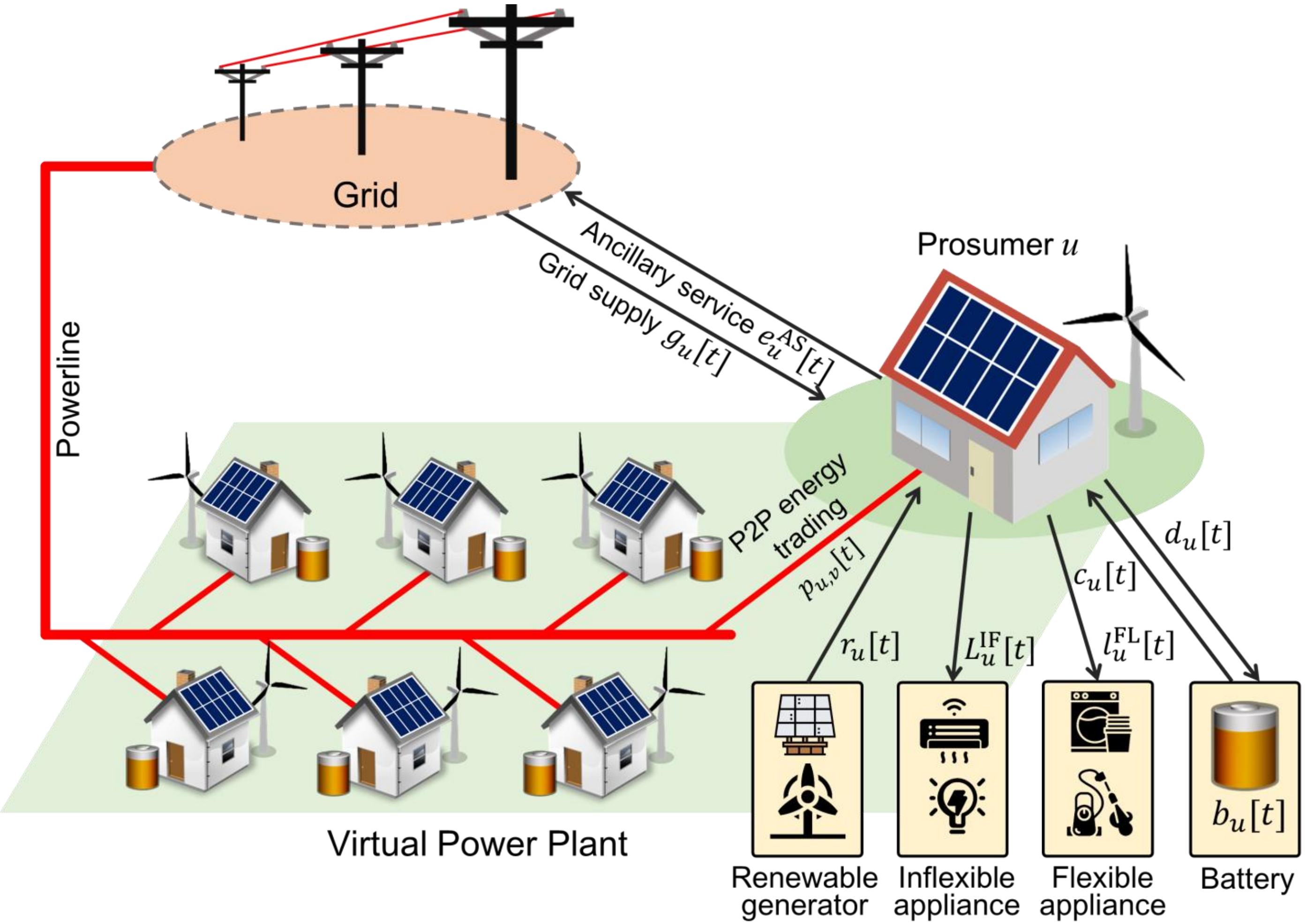
$$C_u = C_u^{\mathrm{G}} + C_u^{\mathrm{FL}} + C_u^{\mathrm{BA}} + C_u^{\mathrm{P2P}} - \mathcal{R}_u^{\mathrm{AS}}$$

Optimization target

The transactive energy management problem:

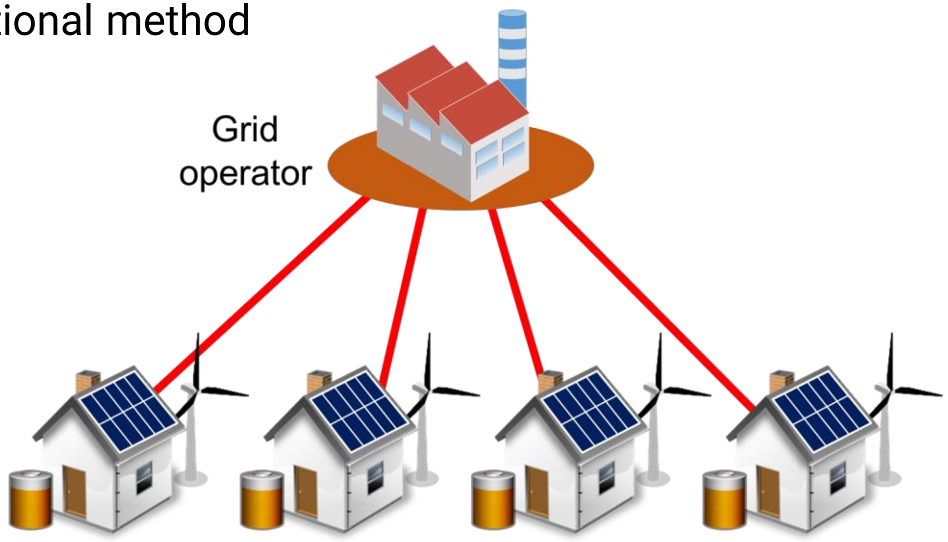
$$\boldsymbol{s}^* = \arg \min_{\{\boldsymbol{g}_u, \boldsymbol{r}_u, \boldsymbol{l}_u^{\mathrm{FL}}, \boldsymbol{c}_u, \boldsymbol{d}_u, \boldsymbol{p}_{u,v\in\mathcal{U}}, \boldsymbol{e}_u^{\mathrm{AS}} | \forall u \in \mathcal{U}\}} \sum_{\forall u \in \mathcal{U}} C_u$$

Optimal DER schedule



Centralized solution VS decentralized solution

Conventional method



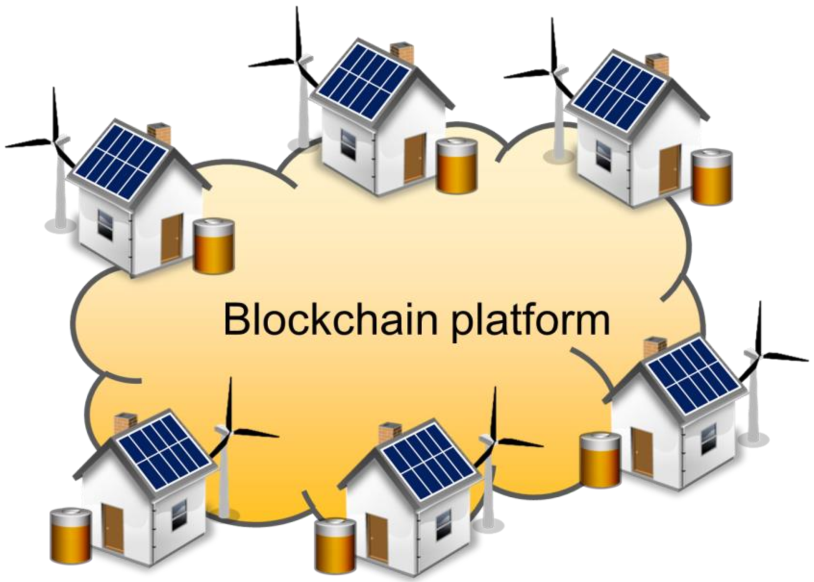
A central coordinator solves the energy management problem:

$$\min_{\{g_u, r_u, l_u^{\mathrm{FL}}, c_u, d_u, p_{u,v\in\mathcal{U}}, e_u^{\mathrm{AS}} | \forall u \in \mathcal{U}\}} \sum_{\forall u \in \mathcal{U}} C_u$$

Drawbacks:

- Single-point failure
- Untrusted black-box operation
- Privacy leakage
- High maintenance cost

Our method



Primal-dual decomposition using the ADMM algorithm

- Primal problem

$$\min \left\{ C_u + \sum_{v\in\mathcal{U}} \sum_{t\in\mathcal{H}} \left[\frac{\rho}{2} \left(p'_{u,v}[t] - p_{u,v}[t]\right)^2 - \lambda_{u,v}[t] p_{u,v}[t] \right] \right\}$$

with variables : $g_u, r_u, l_u^{\mathrm{FL}}, c_u, d_u, p_{u,v\in\mathcal{U}}, e_u^{\mathrm{AS}}$.

- Dual problem

$$\min \sum_{u\in\mathcal{U}} \sum_{v\in\mathcal{U}} \sum_{t\in\mathcal{H}} \left[\frac{\rho}{2} \left(p'_{u,v}[t] - p_{u,v}[t]\right)^2 + \lambda_{u,v}[t] p'_{u,v}[t] \right]$$

with variables : $p'_{u,v}[t], \forall u, v \in \mathcal{U}, \forall t \in \mathcal{H}$,

Blockchain-based transactive energy management

Benefits of using blockchain?

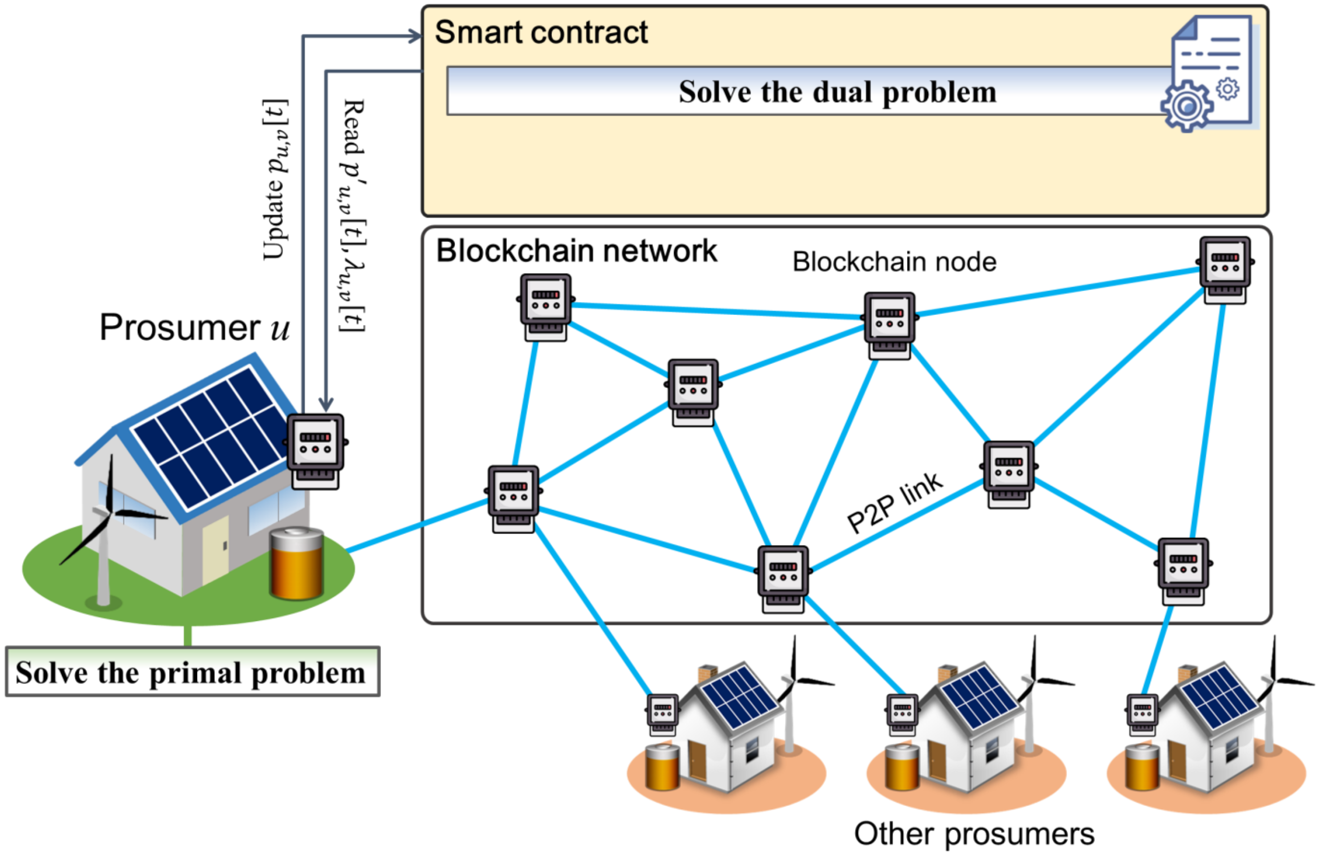
- ✓ A trusted computing platform
- ✓ Low maintenance cost
- ✓ Convenient online payment

Solve the primal problem by the prosumer

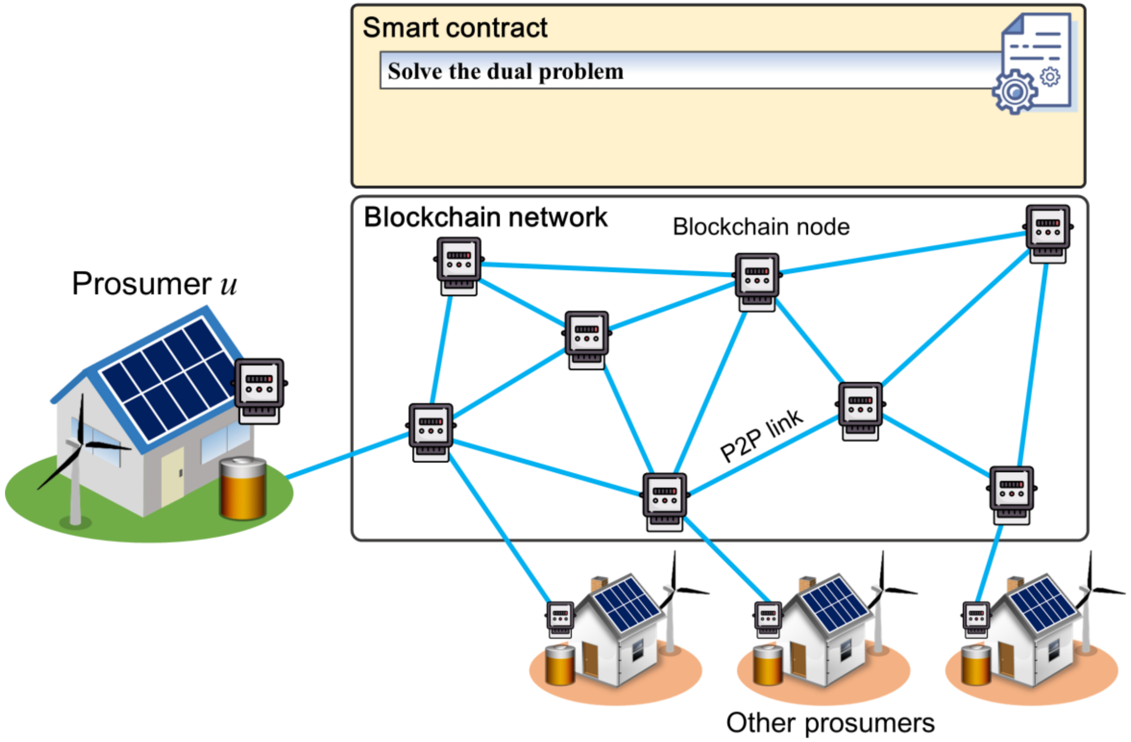
- ✓ Preserve the prosumer's private information

Solve the dual problem using the smart contract

- ✓ Remove the central node
- ✓ Verifiable and trusted computation



Algorithm design



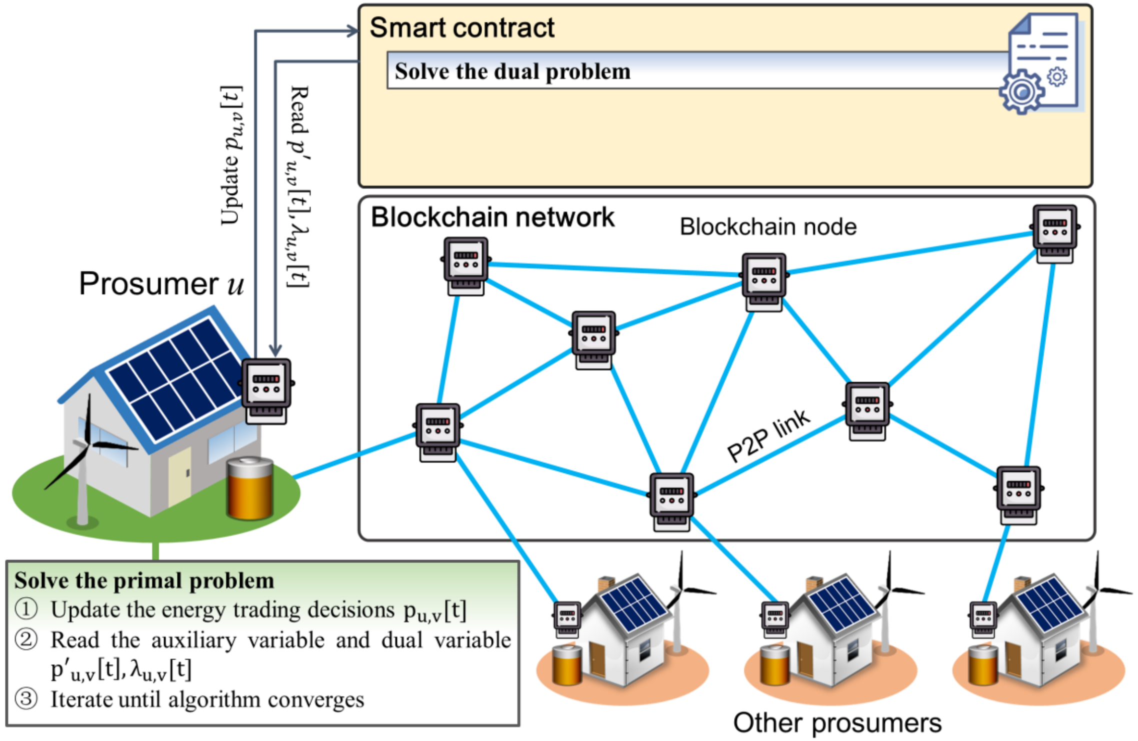
Parameter initialization

Algorithm 1: Transactive energy management

Input: dual variable $\boldsymbol{\lambda}_{u,v}^{(0)}$, auxiliary variable $\boldsymbol{p}'_{u,v}$.
Output: optimal transactive energy schedule $\boldsymbol{s}^*$.

1 Iteration index $k \leftarrow 0$;
2 Convergence threshold $\epsilon \leftarrow 0.000001$;
3 $\boldsymbol{\lambda}_{u,v}^{(0)} \leftarrow \mathbf{0}$, $\boldsymbol{p}'_{u,v} \leftarrow \mathbf{0}$, $\forall u, v \in \mathcal{U}$;

Algorithm design

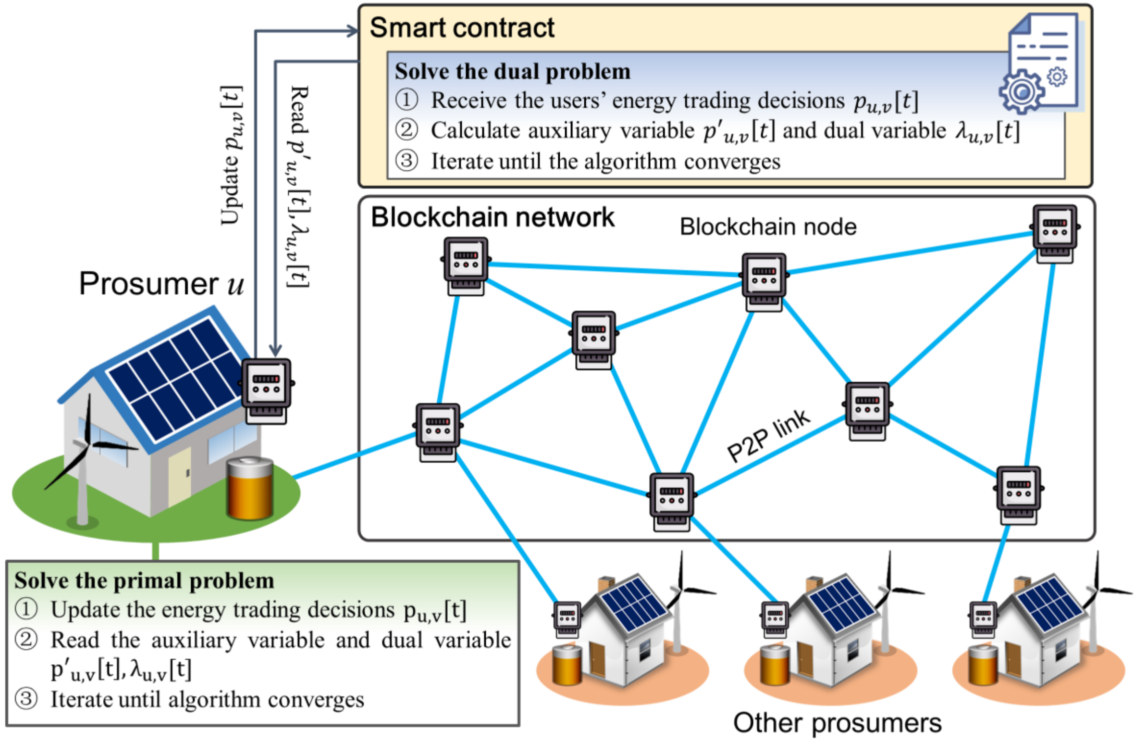


- Prosumer solves the primal problem locally
- With the Octave quadratic programming library

Algorithm 1: Transactive energy management

```
Input: dual variable λ^(0)_{u,v}, auxiliary variable p'_{u,v}.
Output: optimal transactive energy schedule s*.
Iteration index k←0;
Convergence threshold ϵ←0.000001;
λ^(0)_{u,v}←0, p'_{u,v}←0, ∀u, v ∈ 𝒰;
while Σ_{u∈𝒰} Σ_{v∈𝒰} ‖ p'_{u,v} − p_{u,v} ‖≥ ϵ do
    for prosumer u ∈ 𝒰 do
        ▹ Call smart contract Func C to read p'_{u,v} and λ^(k)_{u,v};
        ▹ Solves the primal problem numerically;
        ▹ Call smart contract Func B to update p_{u,v};
    end
end
```

Algorithm design



- The smart contract solves the dual problem
- In Solidity and pre-compiled contracts

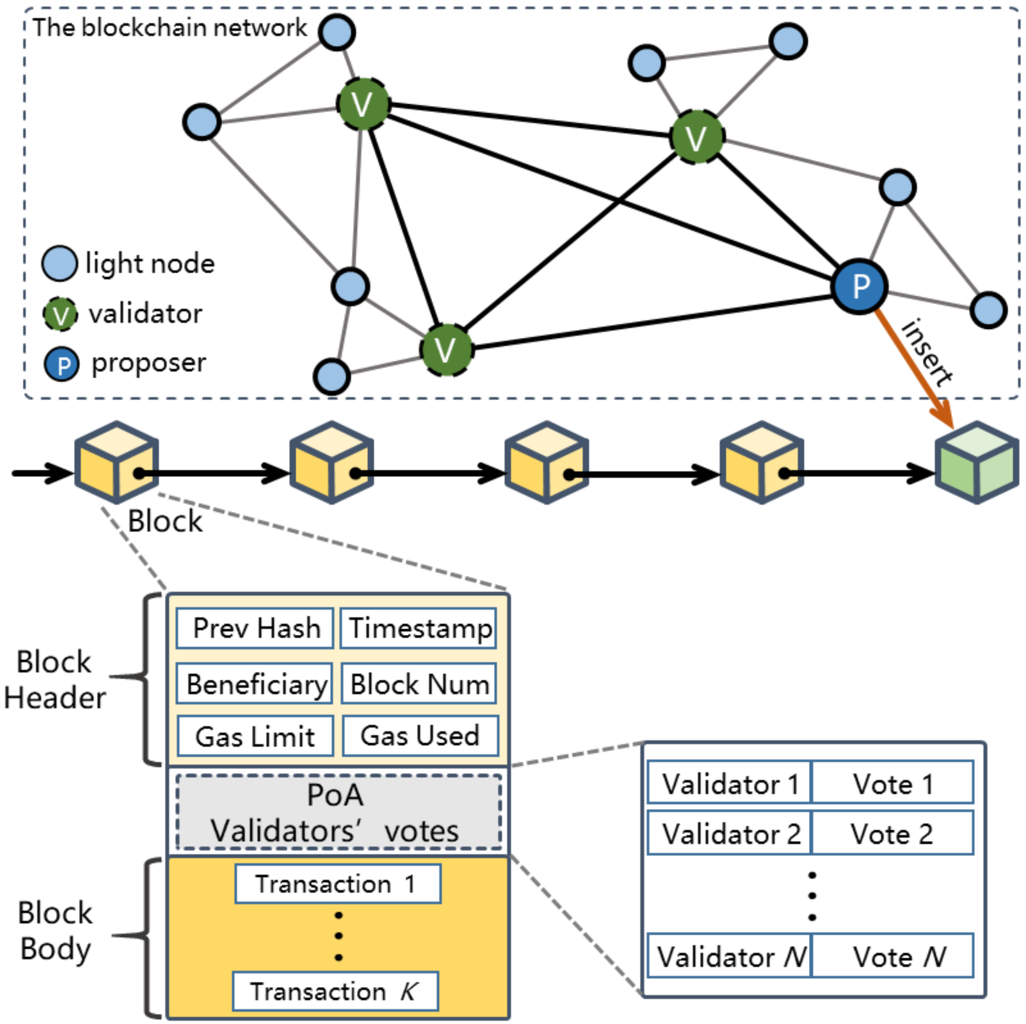
Algorithm 1: Transactive energy management

Input: dual variable $\boldsymbol{\lambda}^{(0)}_{u,v}$, auxiliary variable $\boldsymbol{p}'_{u,v}$.
Output: optimal transactive energy schedule $\boldsymbol{s}^*$.

```
Iteration index k←0;
Convergence threshold ϵ←0.000001;
λ^(0)_{u,v}←0, p'_{u,v}←0, ∀u, v ∈ 𝒰;
while Σ_{u∈𝒰} Σ_{v∈𝒰} ‖ p'_{u,v} − p_{u,v} ‖≥ ϵ do
    for prosumer u ∈ 𝒰 do
        ▹ Call smart contract Func C to read p'_{u,v} and λ^(k)_{u,v};
        ▹ Solves the primal problem numerically;
        ▹ Call smart contract Func B to update p_{u,v};
    end
    Smart contract Func A do
    ▹ Wait for all prosumers to update p_{u,v};
    ▹ Computes the auxiliary variable p'_{u,v};
    ▹ Computes the dual variable λ_{u,v};
    k ← k + 1;
end
```

Design of the blockchain system

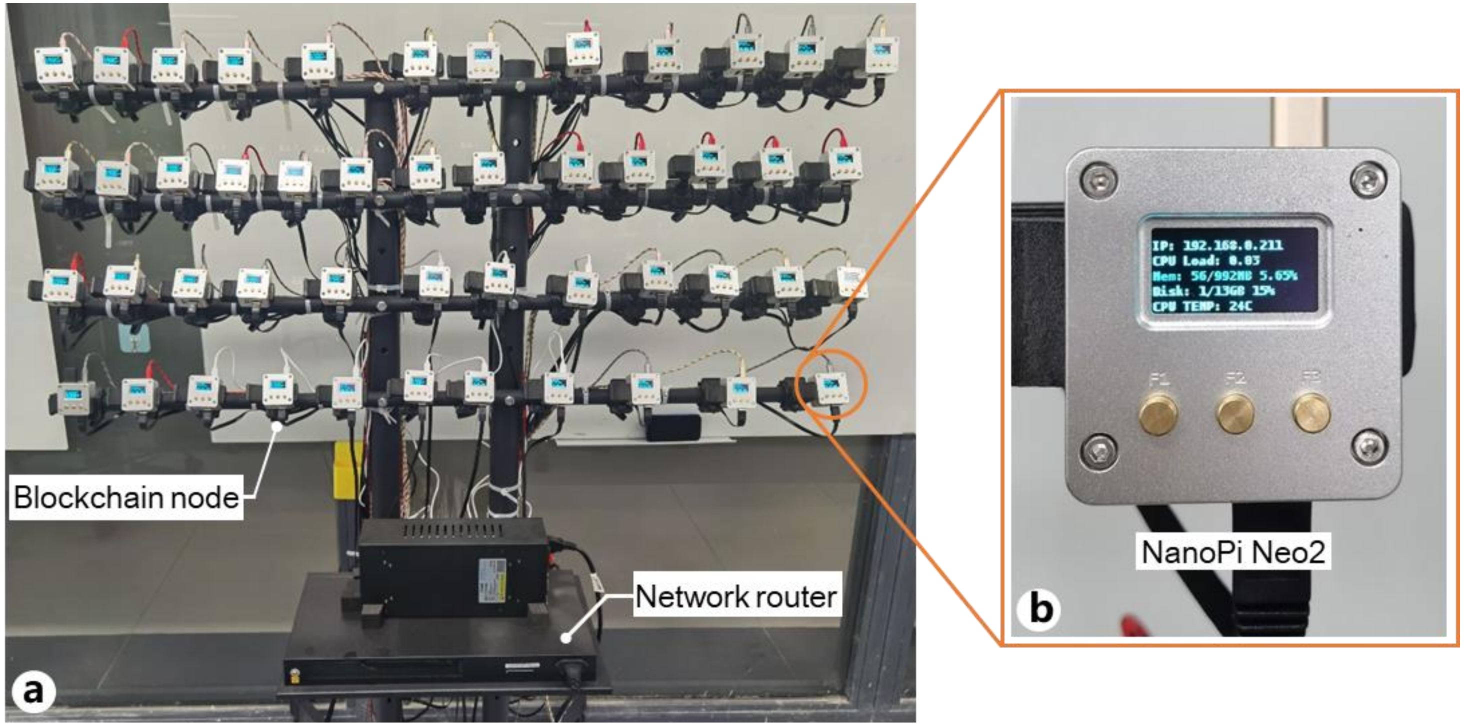
- Run the blockchain node in smart meters
- Implement the blockchain software based on Ethereum
- Adopt the proof-of-authority (PoA) consensus protocol
  - ✓ Validator node
  - ✓ Normal node



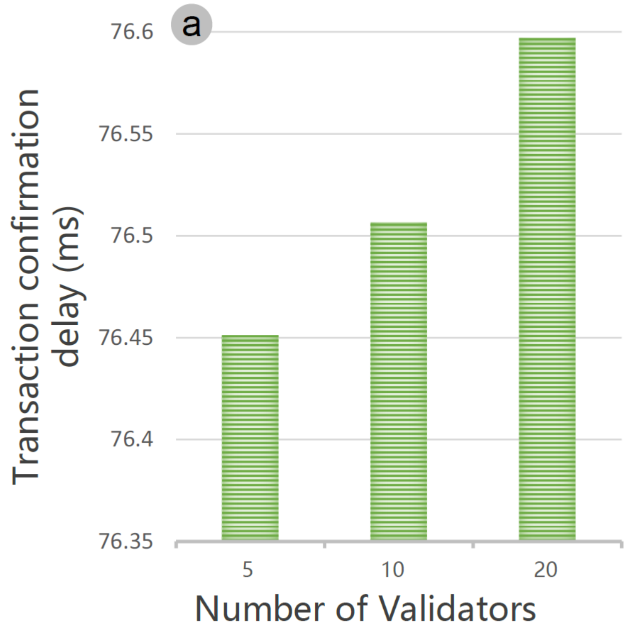
System evaluation

- NanoPi Neo2: an industrial-level embedded device
  - ✓ ARM A53 CPU
  - ✓ 1GB memory
  - ✓ 16GB storage
- A test network of 48 NanoPis
- Resource consumption of a blockchain node

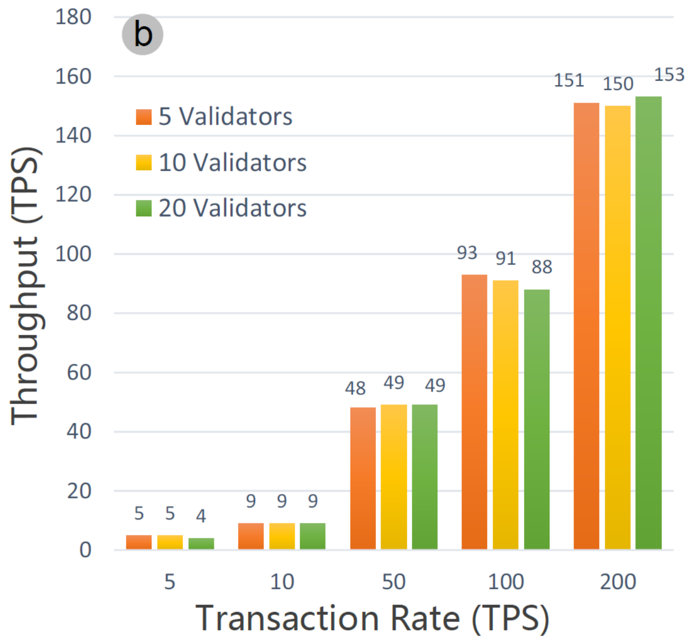
Node Type	CPU	Memory	Storage (Height)
Validator	1.2%	565MB	157MB (33846)
Normal	0.7%	390MB	23MB (20195)



Performance of the blockchain

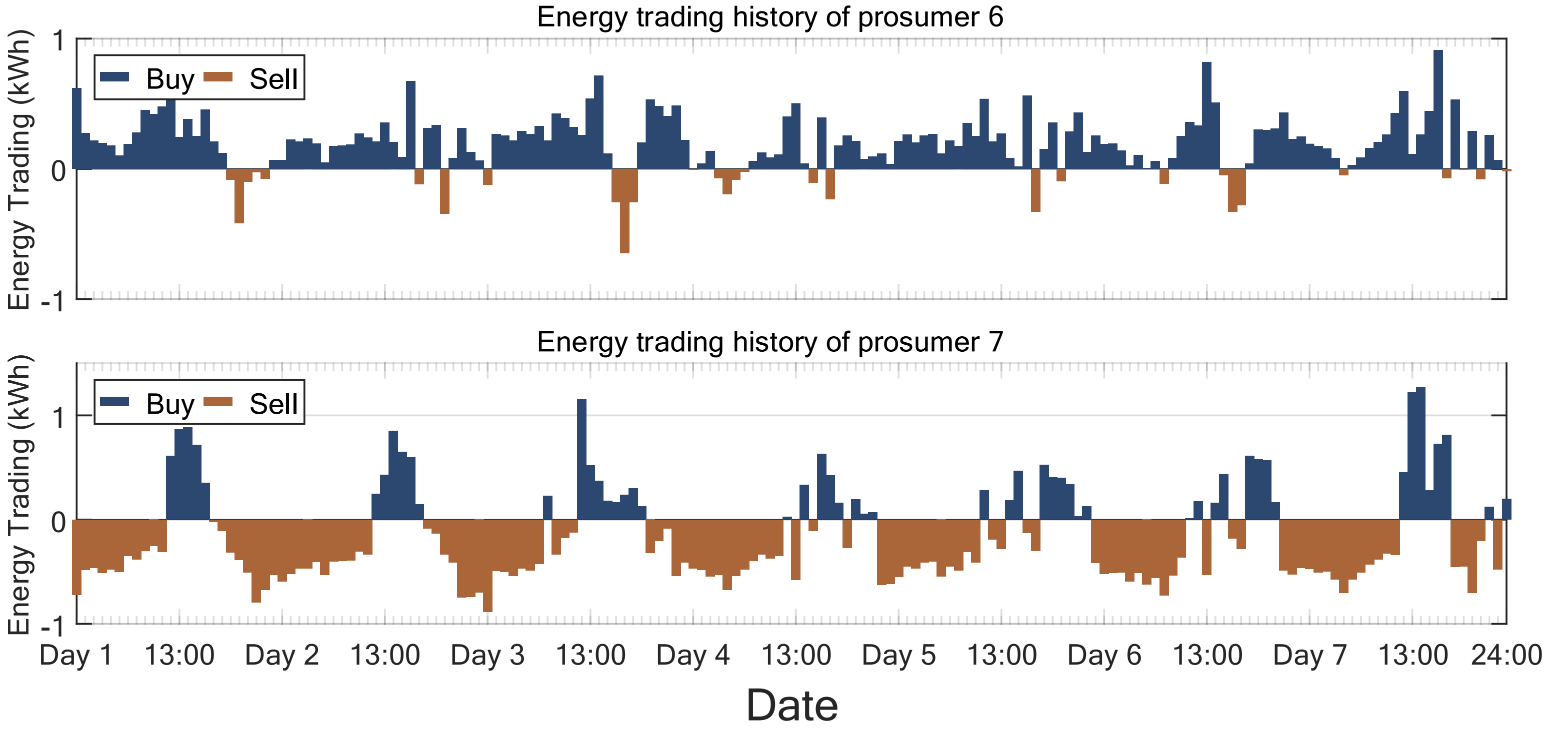


(a) Transaction confirmation delay is about 76ms



(b) Transaction per second saturated at 150TPS

Performance of the transactive energy management algorithm



- Simulation with real-world data collected at Hong Kong
- 10 prosumers during one week
- We observe active energy trading among prosumers
- Optimal transactive energy management

Summary

Conclusion

- We presented a blockchain-based transactive energy management for DERs
- We designed a decentralized optimization algorithm for transactive energy management
- We develop a blockchain for smart meters to support the decentralized algorithm
- Evaluate the method with a test network and real-world data

Future work

- Decentralized transactive energy management algorithm with lower complexity
- High-performance blockchain system for IoT devices
- Consider larger scale of smart grid network

Thank you for your attendance!

Q&A